Anglia Ruskin University

The use of Phonoarthrometry to detect Osteoarthritis in the Human Knee Joint: A Clinical Proof of Concept Study.

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A thesis in partial fulfilment of the requirements of Anglia Ruskin University for the degree of Doctor of Philosophy

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If the work contained in this thesis is seen as a journey, then I would like to thank a number of people who made it a purposeful march rather than an aimless wander.

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ANGLIA RUSKIN UNIVERSITY

ABSTRACT

FACULTY OF HEALTH, SOCIAL CARE AND EDUCATION

DOCTOR OF PHILOSOPHY

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The potential clinical value of sounds and vibrations produced by joints as they move has been studied extensively since 1902 however as of yet no clinically useful device exists. The phonoarthrometer is an experimental prototype diagnostic tool which has the potential to detect joint disorders through interpretation of the sounds produced when the knee joint is moved naturally. The study aims to evaluate the phonoarthrometers' clinical usefulness through its ability to detect osteoarthritis of the human knee joint.

Investigation of the phonoarthrometers' ability to detect osteoarthritis involved taking the prototype device into a clinical environment and using it to test osteoarthritic affected knee joints. A dataset from knee joints defined as normal was also collected for use in the building of the core microstructure database and for use as a comparative control group. The vibration signal of the knee joint was collected via accelerometer sensors placed at the patella and a medial joint line. An electro-goniometer was used to collect the angular data of the knee in motion. All participants were required to complete a set of test protocols designed to gather both loaded and unloaded data from the knee joint. Collected data was then analysed using the phonoarthrometer software.

The phonoarthrometer was able to differentiate an osteoarthritic knee vibration response from a healthy normal knee response. This manifested as a greater level of suppression in the vibration response from the osteoarthritic knee group compared with the normal knee group. Detection between medial and lateral compartment osteoarthritis was possible due to differences in the suppression level of the vibration signal. Determination of the severity of the osteoarthritis in the affected knee was not consistent enough to be conclusive.

The phonoarthrometer in its current state of development would be limited in its usefulness as a diagnostic device. Further improvements to its detection ability are needed to allow the level of detail needed for a clinically useful diagnosis.

Key words: Knee, Joint, Osteoarthritis, Vibration, Arthrometry, Phonoarthrometer

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George Edward Bocking

Chapter 1

A review of the historical literature.

1.1: A History of Joint Vibration Research.

1.11: Early 20th Century Pioneers.

The use of sounds or vibrations being produced naturally from a joint in motion to provide diagnostic information to a clinician is not a new idea. The first published use of this technique was in 1902.

In 1902, William Ernest Blodgett, a Boston Physician, published a paper (Blodgett, 1902) dealing with his successful use of auscultation (listening to the external sounds of the body) as a means to diagnose the injuries and diseases to the knees of the patients he examined. His methods were simple. He would grasp the patient's knee and move it in a gentle backwards (flexion) and forwards (extension) motion and listen to the various sounds that would result with a stethoscope. Observations were recorded in a type of shorthand possibly inspired by Morse code (see figure 1), and he was confident in his ability to offer valuable information of clinical note.

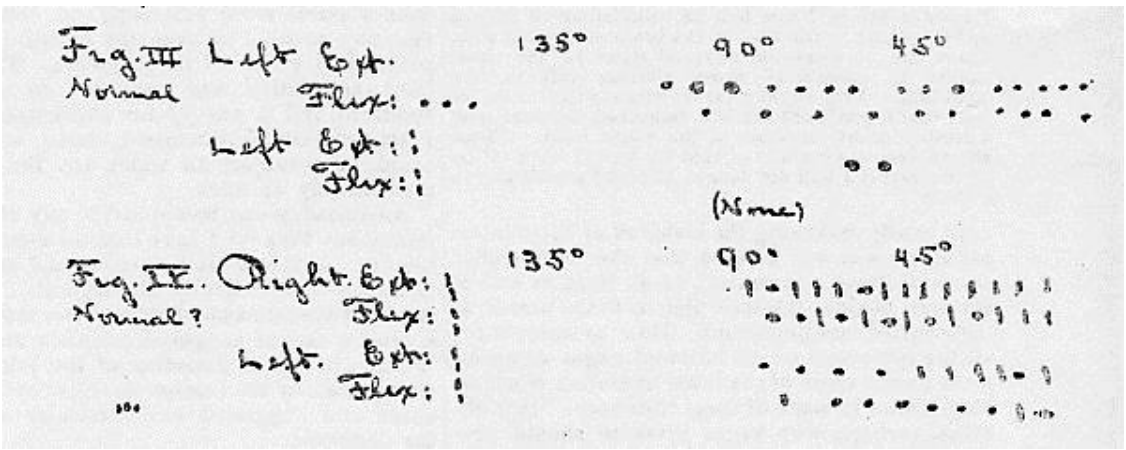

Figure 1. The earliest method of recording a phonoarthrometric trace.
From Blodgett (1902).

It is worth noting Blodgett's primary observations at this point; which are supported by the work of more recent research:

- The joint sounds were prone to be altered, (increased and multiplied) by muscular contraction.
- The first movement provides the greatest noise, the more the joint moves the quieter it becomes.
- To draw any conclusions from auscultation of a joint, it is necessary to know the normal type, range and normal variation of that joint.
- The range of normal variation is very wide.
- Increasing age results in an increase in the intensity of grating sounds.

In time, further work by others followed, with a study of 1600 individuals that showed results of clear medical applicability (Walters, 1929). Later studies introduced oscilloscopes (Steindler, 1937), and electronic microphones (Peylan, 1953).
Although perhaps it is easy to dismiss these early studies as being too crude and to have little value, this would be unwise. It is likely that these earliest of pioneers had trained themselves to be able to filter the rasping sounds they heard and discern subtle differences between the normal and abnormal joints that they examined to aid in their diagnoses.

The difficulty with this is that such skills are not easy to duplicate; a natural talent was probably essential combined with months, if not years, of practice. It was thus unlikely that the technique would achieve routine use. Peylan, recognising this, envisaged a "phonoarthrograph" which would visibly display information from a joint, thus aiding the clinician in diagnosis. (Peylan, 1953). By 1961 the innovation of magnetic tape was used to record the sounds for subsequent detailed frequency analysis (Fischer, 1961).

These early studies all share the optimism that phonoarthrography represented an important innovation in the detection of knee injury and disease. The results obtained, though perhaps positively influenced by bias from the enthusiasm of the authors, do provide a clear indication of useful information being obtainable from the passively generated sounds of the human knee joint. It is also clear that the usefulness of the information was sometimes being degraded by the presence of several sources of

variability such as effusion (an abnormal collection of fluid in a body cavity or space), motion speed, age, muscle activity and prolonged physical activity. Thus the sounds were difficult to interpret with the consistency needed to create a diagnostic process.

It would be another decade before Joint vibration signals would be investigated again. A team working at Akron, Ohio in the United States, led by Professor Mamerto L Chu, performed the first longer term study of phonoarthrometry between 1972 and 1978. The availability of new portable computer systems for research work allowed greater use of frequency analysis and the first use of digital signal processing techniques on the knee joint signals.

Chu's most significant innovation over past work was the, method (by all accounts successful) employed to counter the effects of background noise. Most of Chu's papers describe this (Chu and Gradisar, 1972; Chu et al., 1976 a, b; Chu, Gradisar and Zavodney, 1978b). In essence it consists of employing two microphones; one to record the noises being emitted from the knee, the other to record the ambient noises in the environment. (See Figure 2) The two recordings could then be subtracted from each other by the computer to provide a clean signal from the joint.

The final sentence of Chu's second 1978 study (Chu, Gradisar and Zavodney, 1978b) states that a full clinical trial was needed to properly evaluate the technique. A realistic plan for the development of the technique to wide stream clinical use was suggested. It seemed at this point that within a very few years working phonoarthrography would take its place alongside the other diagnostic methods of that time; yet this proved to be the final journal publication from Chu on phonoarthrography. It would seem that the work had been abandoned shortly after this point; however, it is difficult to determine why in the face of such encouraging results.

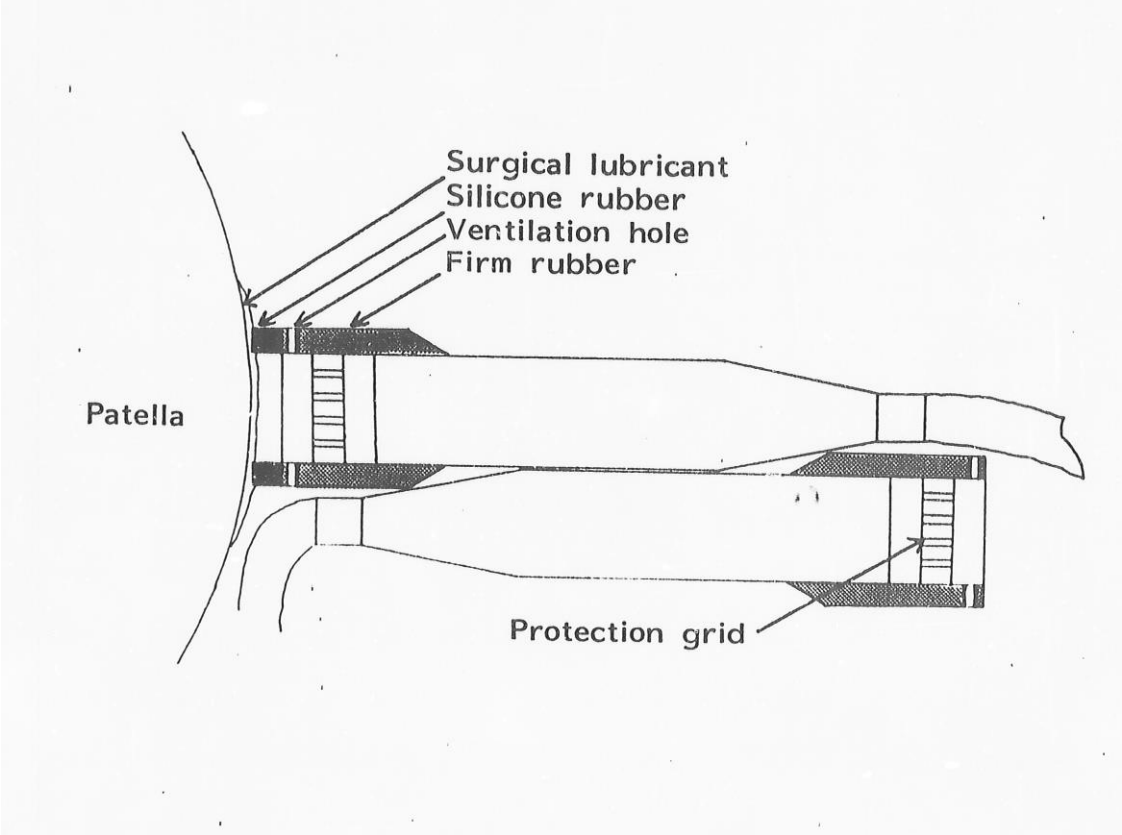

Figure 2: The dual microphone assemblage employed by Chu for background noise cancellation. From Chu et al. (1976b).

Seven years later a short article appeared in the Ohio journal of science (Martin, Mostardi and Gradisar, 1985), which confirmed that a clinical trial had taken place. The trial made use of refined computer systems that used the models of cartilage roughness obtained from animal experimentation (Chu, Gradisar and Mostardi, 1978a; Chu et al., 1976c). Perhaps critically, mention is made that the signal obtained in each case was thought to be unique to the individual. This provides a plausible answer as to why the research was abandoned. To be usable in a clinical environment, phonoarthrography would have to be capable of establishing normal, from abnormal, knee joints across the total population range.

1.12: Queens University Belfast.

Next to enter the research field were the team at Queens University, Belfast who first published in 1981, with the completion of a PhD project undertaken by R.A.B. Mollan (1981), the group remained active in the literature until 1994. The aim of Mollan's PhD

was to investigate the apparent failure of previous work to develop phonoarthrography fully; he also sought to better investigate the concept of background noise identified by Chu et al. (1976a) and its potential impact upon the clinical use of phonoarthrographic signals.

Mollan began by investigating methods for eliminating any extraneous sounds and potential sources of difficulty with the established use of microphones for recording phonoarthrographic traces. He used an anechoic chamber to ensure the quietest possible environment and closely examined the responses of the microphone. A serious problem was identified with the use of microphones; the sounds being emitted from the joint were proving quite difficult to pick up. The microphone was positioned a short distance away from the joint and it seemed likely that much of the sound was being reflected back into the joint at the skin-air interface.

Mollan observed that clinicians were able to better recognise the presence of signals from the joint by touch rather than from using the recorded waveforms. From this important observation an alternate measuring device was tried, the piezoelectric accelerometer. Accelerometers measure physical vibrations, which can be thought of as the mechanical cause of the sound being detected. The device is a contact sensor and does not register background sounds from the environment. These factors appeared to make it an ideal instrument for the investigation of sounds from the knee joint, and indeed Abbott (2008) also concluded an accelerometer provided the best results, with his comparison between an electronic stethoscope and accelerometer.

Having addressed the perceived difficulties of instrumentation, work could be begun in earnest on investigating the joint vibration signals. Results published in 1982 (Mollan, McCullagh and Wilson, 1982) recognised two distinct types of vibration from the knee joint, discrete short time duration high amplitude clicks, as well as a longer duration feature that was termed patella femoral crepitus, consisting of a train of pulses. It was recognised that the crepitus was at its most noticeable between 10 to 20 degrees of flexion, the point often described as the screw home mechanism where the joint rotates and locks into a solid vertical position.

One of the key elements of the research by Queens University Belfast was the view that in order to use the knee joint vibration signals, it was first necessary to understand the mechanism of their generating. This view was developed by W.G Kernohan and explored carefully in his 1983 PhD thesis. (Kernohan, 1983)

Kernohan defines a link between the nature of the surface of articular cartilage (cartilage found covering the ends of bones) and the vibration readings, making particular reference to the concepts of lubrication. He recognised two types within the joint: boundary lubrication and hydrostatic lubrication. He presents a convincing picture of the knee joint as a complex bio-mechanical structure, containing dynamically shifting levels of friction between contacting surfaces as a result of the motion of the joint in the presence of the synovial fluid which acts as a lubricant. The point that Kernohan makes, and it is a critical one, is that the structure of the vibration readings taken from a joint could be directly influenced by the dynamically shifting effects of friction between the surfaces and the lubrication state between them.

Kernohan proposed that cartilage surfaces subjected to such effects would produce irregular, periodic, stick-slip vibrations, a juddering motion resulting from the shifting interplay of force, velocity and friction (Kernohan et al., 1986). Beverland in a 1986 study (Beverland et al., 1986) further quantifies this by linking the patello-femoral crepitus signal to stick slip vibration at the joint interface. These observations would appear to add to the earlier findings of Chu (Chu, Gradisar and Mostardi, 1978a; Chu et al., 1976c), with respect to cartilage roughness.

In parallel with the detailed work taking place on potential sources of the vibration signals, greater investigation of abnormal joints was taking place to develop the diagnostic potential of the technique. Joint angle was obtained from an electro-goniometer, and use of three accelerometers was now being made, allowing tentative locations to be identified for features in the signals through triangulation. In addition to the accelerometer on the patella, accelerometers were also attached to the medial and lateral condyles (projections found at the lower extremity of the femur) (Kernohan, 1983).

Reports of variability by previous researchers were taken very seriously by the team at Queens University and received considerable attention. Several areas were explored; sometimes the issues of variability were made the principle focus of a paper.

Kernohan's 1991 study (Kernohan et al, 1991) reports directly on experiments testing the effect of angular velocity. He noted that the amplitude of the patella click signal increased directly with speed, causing him to investigate the effect of speed on pathological meniscal (cartilaginous structures found in the knee that reduce friction) signals. This, he stated, was essential if reliable diagnostic conclusions were to be drawn from the strength of such signals, such as those suggested by McCoy (McCoy et al., 1987), where excellent results from a study of meniscal tears were reported.

Kernohan concludes by pointing out that the 90% postoperative reduction in signal intensity reported by McCoy (McCoy et al., 1987) cannot be deemed reliable, because a reduction of up to 50% can be achieved simply by altering the speed of movement. He goes on to state that unless joint speed is standardised in all such investigations, the signal level will not reflect accurately the degree of damage to the joint, but will also be a function of the experimental practice. He suggests that there is a need for a standardised, operator-independent test (Kernohan et al, 1991).

Barr's 1994 study (Barr et al., 1994) is the final paper published by the team at Queens University Belfast. In the opening paragraphs he succinctly defines that the problem with using joint vibrations to derive reliable information is that the sounds and vibrations can be affected by numerous influences, few of which are typically normalised. Great variability therefore manifests itself in any recordings of joint vibrations. He goes on to state that the general reluctance for adopting the technique for clinical use is testimony to the failure of researchers adequately to address the problem of variability in vibration signals.

1.13: University of Calgary.

Active in the literature from 1990 until present, a group from the University of Calgary took a very different approach to that of Queens University Belfast. The work at Queens could be summarised as being focussed on investigating the physical sources of joint

vibration signals and their influencing effects upon the resultant output. The new group in Calgary led by Professor Rangaraj Rangayyan, (an expert in electronics and digital signal processing), intended to solve the problems of variability through use of sophisticated signal processing techniques in order to bring phonoarthrography into routine clinical use.

In a detailed review of the literature to date (Frank, Rangayyan and Bell, 1990), Frank demonstrates extensive knowledge of all previous workers in the field; however, the review very much focuses on the more positive aspects of Vibro-Arthrography, as the Calgary team termed their technique. The steady theme of problem investigation by the Queens University Research Team is given little attention beyond mentioning difficulties being attributable to the use of microphones.

If the goal of routine clinical use of Vibro-Arthrography was to be achieved, the development of automated signal pattern identification and classification schemes would be vital. As a first attempt to facilitate this, a neural network was employed by Zhang to attempt to classify knee joint vibration signals (Zhang et al., 1990). A neural net is well suited to the identification of patterns of similarity within complex data and Zhang employed a standard 3 layer system consisting of input, hidden and output layers. The neural net achieved a reported 86% success rate.

In 1992, Zhang dealt with an attempt to formulate a mathematical model for the patello femoral crepitus signal (Zhang et al., 1992); a number of important observations were made, which include:

- Any attempt at using the spectrum of the physiological patellofemoral crepitus signal as a measure for quantifying the knee vibration signals could give an incomplete or misleading result. This is due to the spectrum of a single patellofemoral crepitus pulse not being representative of the signal as a whole.
- Parameters relevant to physiological factors such as the pulse repetition rate and the patellofemoral pulse itself are all sensitive to the angular velocity of knee movement. The patellofemoral pulse is further dependent on the position of the accelerometer and the type of knee movement, (flexion or extension).

He goes on to state that if the effects of angular velocity and other measurable parameters on the spectrum could be determined in some way, or if the angular velocity could be standardised, then the effects of such physiological parameters could be interpreted accordingly from the model developed. This evaluation inspired a more detailed investigation of the susceptibility of knee joint vibration signals to external stimuli. Experiments by Ladly investigating how the effects of increased muscle force and loading history of the joint may affect the resulting joint vibration signal took place (Ladly et al., 1993). Ladly concluded that increased muscle activity had little affect on the joint vibration signal, although the loading history of the joint did have an affect. These results match those of Mollan (Mollan et al., 1983), McCrea (1984), and Kernohan (Kernohan et al., 1986). Ladly attempted to localise the source of the signals through the use of three accelerometers and measurement of resulting time delays for a signal reaching each sensor. The technique, described in more detail by Shen (Shen et al., 1995), mirrors that of Kernohan (1983).

The initial observations by Zhang in 1992 (Zhang et al., 1992) on the sensitivity of the signal to external stimuli are further expanded upon by Tavathia (Tavathia et al., 1992), where he identifies the knee joint vibration signals as being non-stationary in nature. He defines this by identifying that the regions of the joint surfaces coming into contact are different at each angle position during the swing. Also the quality of the joint surfaces coming into contact may change with joint angle. This means that signals of different characteristics will be produced at different joint angles, hence the term non-stationary. He goes on to state that all traditional spectrum estimation methods assume the signals to be stationary in nature. This is not the case with knee joint vibration signals, thus making techniques dependent on such factors inappropriate.

In the most recent paper produced by this team (Rangayyan and Wu, 2010), Rangayyan reviews his previous work, which included a vast array of signal processing techniques. These included autoregressive modelling, cepstral coefficients, time frequency distributions, and wavelet packet decomposition. He concludes that they all fail to characterise the joint vibration signals adequately. His most recent work uses a simpler technique, though does employ a neural net, and he reports a 77.53% success rate in classifying joints between normal and abnormal. He goes on to state that a higher

accuracy would be essential before clinical application could be adopted. He also confirms that the variability within the signals is not being adequately addressed as yet.

Further papers since 2010 reveal a collaboration between the Canadian group and Xiamen University, China. This work all uses the same historic database of 89 knee joint signals as used by the group in previous work. They use various variability analysis techniques including fractal analysis, bivariate feature distribution estimation and dynamic weighted classifier fusion (Wu and Krishnan, 2011; Rangayyan et al., 2012; Cai et al., 2013; Wu et al., 2013). They report classification accuracies of 80.9- 88.76 % however given that there is no conclusion that these are clinically applicable, or proposed plans for a greater clinical evaluation it would seem that these techniques suffer from the same problems as encountered previously by Rangayyan.

1.14: Other work of note.

A short series of papers were produced by the University of Taiwan between 1993 and 2000. Much of the early work was very similar to that of Queens University Belfast, however, later papers made two significant contributions to the field. The first was the introduction of a Biodex Isokinetic Dynamometer into their data collection procedures (Jiang et al., 1994). An image of this device is presented as figure 3, obtained from the Biodex website. Clearly this complex device was intended to normalise the effects of angular velocity; whether this was actually successful is difficult to determine, but it is reasonable to assume that it was not since no functioning prototype phonoarthrographic device was developed for clinical use that incorporates the Biodex Isokinetic Dynamometer. The second contribution was by Jiang in 2000 (Jiang, Lee and Yuan, 2000), and is unique in the published literature, being the only study ever published on artificial knee joints.

Figure 3. Biodex Isokinetic Dynamometer. From http://www.biodex.com/rehab/system4/system4_feat.htm

1.15: Recent developments.

Several papers have appeared more recently by new researchers to the field, and it is vital they be placed in the proper context with the material already published in the field.

A study by Kargus in 2007 (Kargus et al., 2007) deals uniquely with the shoulder joint, a joint that had thus far not received attention by researchers working on joint vibration. The paper references papers from all the main groups that have worked in the field (Belfast, Calgary, Taiwan and America). An area of immediate concern with the review by Kargus (Kargus et al., 2007) is that no mention is made of any of the difficulties encountered by those previous researchers, despite such difficulties being clearly reported in their papers. One could gain the impression that joint vibration analysis was a successfully operating procedure with regard to the hip, knee and the temperomandibular joint. The literature shows very clearly that this is not the case at all.

This same issue occurs with the recent study by Mascaro in 2009 (Mascaro et al., 2009), again making no reference to the problems with the technique. His study on osteoarthritic knees reports on work using what they term Acoustic Emission or AE, linking this to

engineering research that uses the high frequency burst associated with structural failure in materials such as concrete beams or engine parts. A series of papers from the University of Central Lancaster continue with this method (Shark, Chen and Goodacre, 2010; 2011) and although this would seem an interesting approach, when one balances this study against the work that has already been published in this field it is hard to conclude that this study offers anything new.

Kim's 2009 paper (Kim et al., 2009) deals with work following a similar signal processing approach to that employed by Professor Rangaraj Rangayyan's more recent papers. (Mu, Nandi and Rangayyan, 2008; Rangayyan and Wu, 2010) Interestingly they do not employ accelerometers, choosing to use a digital stethoscope instead. Their results seem very convincing, but it should be borne in mind that past results have seemed equally convincing in this field. To their credit they make clear statements regarding the issues of variability and the non-stationary nature of the signal structure as a hindrance to development of a technique.

Interestingly recent publications show two groups currently working on the use of acoustic and vibration techniques in joints other than the knee and relating to specific conditions found in these joints.

The first is from the University of Tennessee, this group are investigating the use of vibrations combined with gait kinematics of artificial hip joints as a method for the early detection of joint prosthesis loosening. Their early results show promise but conclude that further work would be required to account for a wider number of conditions affecting the hip joint (Glaser et al., 2010).

The second group is from Sun Yat-sen University, Guangzhou, China. They are concerned with joint vibrations produced by the temporomandibular joint. Their results suggest that a simple division based on the ‘loudness’ of noise is possible to determine a healthy from an affected joint (Li, Lin and Wang, 2009; Huang, Lin, and Li, 2011). Whether this is the case, suggesting that analysis of the temporomandibular joint is much simpler than that of the knee, or whether as the research develops similar problems as those related to knee analysis will be encountered remains to be seen.

Both these areas of research show good results for diagnosis of specific conditions in joints other than the knee but given the specificity of the research it is doubtful that they will be applicable in any meaningful way to knee joint analysis.

One last paper is from Japan, this research seems to be at an early development phase, it attempts to classify the knee vibration responses from sitting and standing movements (Tanaka and Hoshiyama, 2012). It concludes that vibroarthrographic signals from osteoarthritic knees are higher than those from healthy knees; it would seem that at this early stage of development they have yet to encounter the variability found in these signals that is so widely reported in other literature. They do however acknowledge that vibroarthrographic signals may be influenced by the angular velocity of the joint.

It is clear that the analysis of joint vibration signals is a topic that has received considerable interest in the literature since the first paper in 1902. (Blodgett, 1902). Equally clear from the results of this review is that previous attempts made to develop the study of joint vibration into a routine clinical procedure would appear to have failed. Each of the main research groups that have investigated the technique follows a very similar pattern of tone within their publications. Early papers are filled with enthusiasm and optimism, first attempts to match known abnormal joint vibration signals to the results of clinical investigation are claimed to be successful, with clear differences being reported, at this point however problems are encountered.

A recurrent theme throughout many of the papers published on joint vibration signals identify that the signals are subject to intense levels of variability.
. In the thesis by Abbott (2008), from which this study continues directly, an experimental phonoarthrometer was produced. This incorporates software specially designed to account for the variability in joint vibration signals. His work shows clear evidence of the software's ability to account for the variability, through the 2000 recordings of knee motion from 23 normal individuals that are all characterised as normal by the instrument. A handful of abnormal knee responses are presented, who were examined under blinded conditions, and have clear abnormal responses, with differing abnormal patterns between three individuals with osteoarthritis, ligament instability and meniscal tear. However, although these results are promising, they only show that the joint vibration signal is being normalised, and make no case for clinical usefulness of the signal.

Abbott (2008) was able to design and develop a prototype phonoarthrometer by finding an apparent solution to the severe technical barriers that had prevented prior development of a usable device. His PhD was focussed on the means by which these barriers were

overcome, rather than clinical use of the instrument. It concluded with limited but highly promising clinical evidence that his instrument could have useful clinical application, but did not provide conclusive evidence of this. To summarise, Abbott (2008) was able to prove that the technical issues preventing phonoarthrometry being used in health care had been solved, however the question of whether the sounds from joints could actually be used to gain useful clinical information remained unanswered.

1.16: Conclusions.

In conclusion, it can be said that the potential clinical value of sounds and vibrations produced by joints as they move has been studied extensively since 1902, with 76 publications identified in the literature to date. If perfected the technique would have clear advantages to current medical imaging technology such as Magnetic resonance imaging (MRI), due to its speed, low cost, and non-invasive nature. Queens University Belfast between 1981 and 1994, and the University of Calgary between 1990 and the present day produced the most significant work in the field to date. When examined as a whole, the literature reveals that there are significant technical barriers to successful implementation of this technology. Although this is clearly reported by the Belfast and Calgary research teams, this review asserts that recent published work in this field makes insufficient reference to these issues, which could result in an over optimistic view being gained of the current state of this potentially invaluable technique. The barriers are serious, and are the result of intense variability within the recorded signals being caused by the differing characteristics of joint surface and forces throughout the motion of the joint. The signals are most commonly described as being non-stationary in nature. Until these issues of variability are shown to be adequately dealt with, and clear evidence of clinical usefulness to orthopaedic medicine demonstrated, it will not be possible to move the field forwards.

In each of the main research groups investigated, the technique follows a very similar pattern of tone within their publications. Early papers are filled with enthusiasm and optimism and first attempts to match known abnormal joint vibration signals to the results of clinical investigation are claimed to be successful. However, from this point onwards problems are encountered in the development of a clinically useful device.

Almost all papers published on phonoarthrometry identify that the signals from the joint are subject to intense levels of variability. Much has been published on joint vibration but until these difficulties of variability have been accounted for the results thus far presented must be treated with scepticism. In final conclusion, the ultimate question of whether joint vibration signals can actually reliably distinguish between normal and abnormal joints remains unanswered by the literature at this time.

As Barr was forced to conclude, (Barr et al., 1994) the general reluctance for adopting the technique for clinical use is testimony to the failure of researchers to address the problem of variability in vibrational signals adequately. The ultimate question of whether joint vibration signals can actually reliably distinguish between normal and abnormal joints currently remains unanswered by the literature.

Chapter 2

The human knee joint and osteoarthritis

2.1: Overview of knee joint anatomy

The following section gives an overview of the complex internal structure of a knee joint. It should not be seen as a definitive examination of the knee's anatomy; any clinically recognised medical or orthopaedic text book will give a much more complete account of the knee's anatomy; indeed many have complete chapters dedicated to this subject. Instead it should be considered as an introductory guide to explain the context of the area of research. A diagram of the main anatomy of the knee (figure 4) is included for reference.

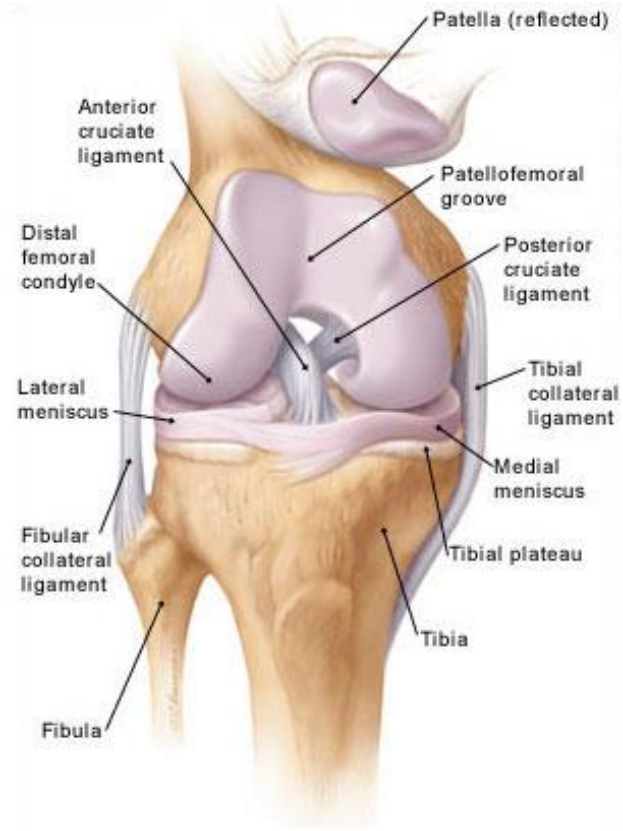

Figure 4. Anatomy of the knee. From Tandeter et al. 1999

The knee joint is the largest joint in the body. It is extremely elaborate and includes three articulating surfaces. In truth these articulating surfaces form two distinct joints, the tibiofemoral and patellofemoral joint, contained within a single joint capsule (Dutton,

2008) and as such form what can be termed a large diarthroidal joint. The joint itself can be seen to be made up of the distal end of the femur, the proximal end of the tibia, the patella (kneecap), joint capsule and synovium, various ligaments, cartilage and intra-articular menisci.

The tibiofemoral joint is formed from the distal end of the femur (femoral condyles) and the proximal end of the tibia (tibial plateau). It is a modified hinge joint with two degrees of freedom (Magee, 2008). The articular surfaces of the femur and tibia are not congruent, enabling the bones to move different amounts as guided by the muscles and ligaments; however the two bones approach congruency in the full extension position (Magee, 2008). The arrangement of the knee allows for the joint to function as a hinge through most of its range of motion (greater than 30^{o}) though uniquely, it also permits the medial side of the femur to rotate on the tibia when extended to less than 30^{o} This is often termed the screw home mechanism or the arc of terminal extension which allows for greater stability of the joint when fully extended (Magee, 2008).

The patellofemoral joint is a complex articulation. The patella itself is a hard, sesamoid (a bone embedded in a tendon) bone, embedded in the tendon of the quadriceps femoris muscle above and the patellar tendon below (Dutton, 2008). Its posterior surface is covered in a layer of cartilage that is the thickest cartilage found in the body (Magee, 2008). The patellofemoral joint acts as a fulcrum to improve the efficiency of the quadriceps in extending the leg during the last 30 degrees of extension. It also guides the quadriceps (or patella) tendon, decreases friction in the quadriceps mechanism, controls capsular tension in the knee and acts as a protection for the femoral condyles.

The joint capsule can be thought of as a balloon that surrounds the entire knee; it is composed of a strong, thin fibrous membrane the lining of which is known as the synovium (Halpern, 2004). The capsule itself is filled with synovial fluid; this provides lubrication for the articular cartilage and supplies the inside of the joint with nutrients. The synovial fluid has a consistency and appearance similar to egg albumen. It provides a superior lubricating system, which permits a remarkably frictionless interaction at the articulating surfaces. A lubricated cartilaginous articulation has a coefficient of friction of 0.002 that compares with ice on ice, which has a coefficient of friction of 0.03 (Dutton, 2008).

The bones are connected to one another and stabilised by the four major ligaments of the knee. The anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) are found in the centre of the joint complex and serve to connect the femur to the tibia. The medial collateral ligament (MCL) is located on the inside of the leg and connects femur to tibia; the lateral collateral ligament (LCL) is found on the outside of the leg and connects femur to the fibula. Ligaments play a key role in providing passive stability to the joint throughout its whole range of motion. Each ligament provides stability and restrains knee motion in more than one degree of freedom, while the overall joint stability depends on the contributions of the individual ligaments and their interactions (Souza and Doan, 2010).

The bones of the knee are cushioned by cartilage, within the knee two types are found; articular cartilage and meniscal cartilage (forming the menisci) (Athanasou, 2001).

Articular cartilage is a complex anatomic structure with a biochemical make-up that directly dictates the fundamental characteristics of the tissue (Saadat, Link and Ma, 2010). Articular cartilage covers the ends of the femur and tibia and the posterior surface of the patella. It protects these surfaces of the bones by absorbing shock, providing a cushion and a smooth surface that facilitates movement (Souza and Doan, 2010)

When examined from inside a synovial joint, normal articular cartilage appears as a slick, firm surface that resists deformation. The primary function of cartilage is not to absorb energy through deformation, but to distribute the range of forces equally to the subchondral bone plates, and provide minimal friction during motion whilst the loads are transferred (Souza and Doan, 2010). Due to the complex mechanical demands placed upon the articular cartilage it displays unique morphological and biomechanical properties that are as yet unable to be completely replicated by any artificial material. The second type of cartilage, meniscal cartilage, is used to form the two menisci found within the knee joint complex (figure 5). These menisci sit on the tibial plateau, the medial meniscus is C-shaped and found on the medial side edge of the tibial plateau, the lateral meniscus is more semicircular or half moon shaped and found on the lateral side edge of the tibial plateau (Athanasou, 2001). The menisci cover the peripheral two thirds of the articular surfaces of the tibial plateau and they are often thought of as extensions of

the tibial articular surface. The surface of the meniscus resting on the tibial plateau is relatively flat and a conforming articular surface is created for the femoral condyle by the concave proximal surface. Both menisci are firmly attached to the tibia through the anterior and posterior horns, when the femoral condyles roll backwards on the tibial plateau during knee flexion, the menisci follow the shape of the femoral condyles and slide backwards on the tibial plateau (Souza and Doan, 2010).

The menisci have several functions within the knee; they aid lubrication and nutrition of the joint, act as shock absorbers spreading the stress over the articular cartilage below thus reducing cartilage wear and they make the joint more congruent thereby improving weight distribution by increasing the area of contact between the femur and tibia (Souza and Doan, 2010).

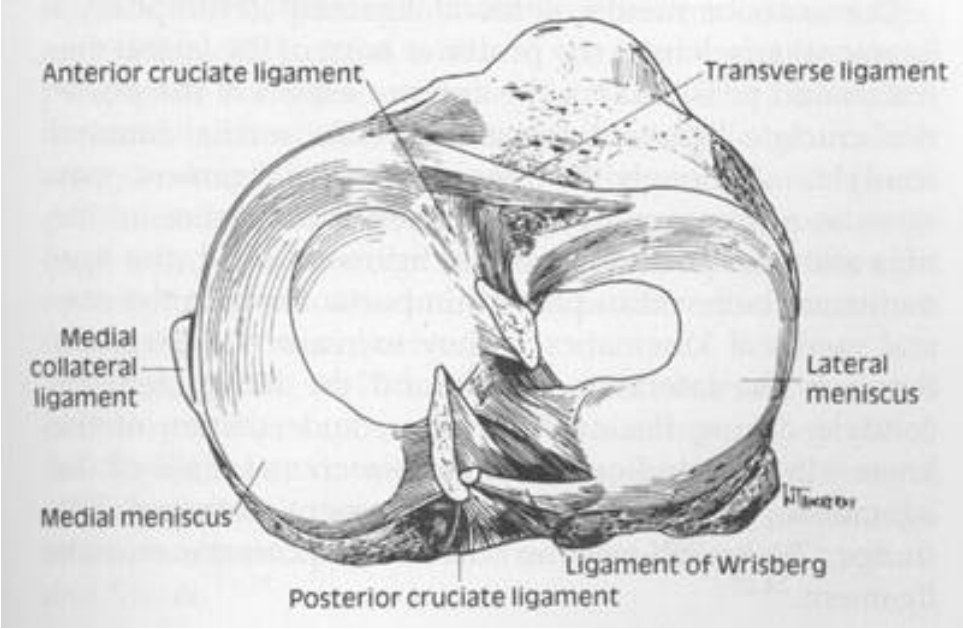

Figure 5: Schematic axial view of the tibial plateau, demonstrating the medial and lateral menisci. From Warren et al., 1986.

2.2: Osteoarthritis

2.21: What is osteoarthritis?

No single terminology or classification system of degenerative joint disease is universally accepted (Arden, Arden and Hunter, 2008). “Arthrosis” refers to mechanical loss of articular cartilage while “arthritis” refers to joint inflammation in association with arthrosis. Originally, the term “arthritis deformans” was used as a descriptive term for both degenerative arthritis and rheumatoid arthritis. However, since joint deformities can accompany many articular processes, this term is not acceptable. Presently, “degenerative arthritis,” “degenerative joint disease” and “osteoarthritis” are used frequently, though “degenerative joint disease” is the best general phrase to describe degenerative processes in any type of articulation, with “osteoarthritis” being reserved for degenerative disease of synovial joints, such as the knee (Saadat, Bolbos and Ries, 2010).

The term “osteoarthritis” implies an inflammatory disease. However, although inflammatory cells may be present, osteoarthritis is considered to be an intrinsic disease of articular cartilage in which biochemical and metabolic alterations result in its breakdown. Osteoarthritis is, simply described, joint failure; a disease in which all structures of the joint have undergone pathological change, often in concert resulting in degeneration of the articular cartilage in the synovial joints(Athanasou, 2001). Osteoarthritis as a disease is characterized by development of fissures, cracks, and general thinning of the joint cartilage, damage to the bones of the joint, hypertrophy of cartilage and synovial inflammation (Brenner et al., 2003).

Osteoarthritis is the most common joint disease, it is estimated that 70-85% of people over the age of 55 are afflicted with osteoarthritis (Dutton 2008) however, most are asymptomatic with the prevalence of symptomatic osteoarthritis being around 20% in the western world. (Marshland and Kapoor, 2004)

Osteoarthritis or joint degeneration occurs when the articular cartilage wears out, or is worn down so that it works much less efficiently. When the cartilage wears out, it decreases in size or volume. Without cartilage or with less cartilage, bones lose their shock-absorbing buffers and begin to rub against each other (Gilbert, 2003). The most

common joints to develop osteoarthritis are the hips, knees, back, neck, and hands, but the process can occur in almost any joint (Marshland and Kapoor, 2004). In osteoarthritis of the knee, joint pain usually develops during weight bearing exercise as the damaged cartilage is unable to provide adequate shock absorption. As the disease progresses, changes also occur in the muscles and bones around the affected knee joint (Dutton, 2008).

Osteoarthritis manifests itself as hyaline articular cartilage loss, present in a focal and, initially, non-uniform manner. This is accompanied by increasing thickness and sclerosis of the subchondral bony plate, by outgrowth of osteophytes at the joint margin and by stretching of the articular capsule; mild synovitis may also be experienced (Lane and Wallace, 2002). Weakness of muscles around the joint may also be found but whether this is due to the disease or due to lack of exercise from the
pain experienced when using the joint is unclear. Specific to the knees, meniscal degeneration is also seen as part of the disease (Saadat, Bolbos and Ries, 2010).

Dramatic spontaneous restoration of the joint space in osteoarthritis is rare, although limited fibrocartilaginous repair is common (Buck et al., 2009). Regeneration of the joint space seems to be associated with peripheral osteophyte formation at the joint margin. An osteophyte which consists of new cartilage and bone likely forms in response to abnormal stresses on the joint margin, although its formation may also occur as a part of the aging process. There is experimental evidence that osteophyte formation is related to instability of joints and its growth has been described as part of the attempt of a synovial joint to adapt to injury, limiting excess movement and helping to recreate a viable joint surface (Lane and Wallace, 2002).

Two types of osteoarthritis are commonly recognized: primary osteoarthritis and secondary osteoarthritis.

Primary osteoarthritis, the most common form, has no known cause, although it appears to be related to aging and heredity. It is often referred to as a "wear and tear" disease as it was formerly thought to be the inevitable consequence of usage of the joint throughout life (Athanasou, 2001). It most often affects the distal interphalangeal joints and, less often, the proximal interphalangeal joints of the hands, the hip, the knee and the

metatarsophalangeal and tarsometatarsal joints of the feet. In addition, the cervical and lumbar spine may be affected (Athanasou, 2001).

For many years, osteoarthritis has been regarded as a "wear and-tear" or "degenerative" condition, a view supported by epidemiological surveys that demonstrated associations with certain occupations and life choices, and its increased prevalence with advancing age (Athanasou, 2001).

Established risk factors include physically demanding occupations, particularly in jobs that involve kneeling or squatting, certain sports, older age, female sex, evidence of osteoarthritis in other joints, obesity, genetic factors and family history and previous injury or surgery of the knee (Arden, Arden and Hunter, 2008).

Before the age of 50, men have a higher prevalence and incidence of this disease than women, but after this age women have a higher prevalence and incidence (Saadat, Bolbos and Ries, 2010). Increasing age does not appear to be an absolute risk factor in the development of osteoarthritis as not every elderly person develops osteoarthritis (Marshland and Kapoor, 2004). The increase in the incidence and prevalence of osteoarthritis with age is likely to be a consequence of several biological changes that occur with aging. Amongst these are a decreased responsiveness of chondrocytes (the cells responsible for production of the cartilage) to growth factors that stimulate repair, an increase in the laxity of the ligaments around the joints, making older joints relatively unstable and, therefore, more susceptible to injury. This leads to the failure of the major shock absorbing menisci and articular cartilage protectors of the joint. Concurrent to this is a gradual decrease in strength and a slowing of peripheral neurologic responses, both of which protect the joint (Dutton, 2008). Osteoarthritis is therefore not a passive process of joint wear and tear but a metabolically active process. Abundant evidence supports the importance of genetic factors in some subgroups of osteoarthritis (Braga et al., 2009).

Secondary osteoarthritis is considered to result from previously existing underlying factors. This classification is, however, widely regarded as misleading. Careful evaluation of many examples of primary "idiopathic" Osteoarthritis reveals an underlying cause, which was initially overlooked or misdiagnosed (Athanasou, 2001). It appears likely that primary degenerative joint disease does not truly exist and this classification stems from

our limited understanding of the disease etiopathology and diagnostic capabilities (Saadat, Bolbos and Ries, 2010).

Secondary osteoarthritis may occur in any joint as a result of articular injury. These injuries include fracture, repetitive joint use, obesity (particularly the knee), or metabolic disease (osteoporosis, osteomalacia). Importantly secondary osteoarthritis may occur at any age (Athanasou, 2001).

Secondary osteoarthritis is often seen in patients with other forms of arthritis, it is commonly seen in patients with other rheumatic disorders. Most of the time this finding is coincidental, but occasionally it can be related. Serious, ongoing, chronic inflammatory processes could be considered to be a form of trauma to the bone and can initiate premature or accelerated osteoarthritis at its areas of involvement (Brenner et al., 2003). Examples of significant inflammation initiating an osteoarthritic response occur in bone infections, frostbite, repeated steroid injections into a joint, and rheumatoid arthritis.

2.3: Generation of sound in the knee joint

Described in simple terms sound is a mechanical vibration that propagates as a mechanical wave of pressure and displacement, through a medium (such as air or water) (Fletcher 1992). Such vibrations are caused due to the frictional effects of any two surfaces as they move against each other. Smooth surfaces with a corresponding low coefficients of friction moving against each other produce less friction and thus less noise, conversely rough surfaces will produce high friction levels and will produce sound of a greater magnitude, one example would be the difference in sound of two sheets of smooth paper being rubbed against each other (relatively quiet) as opposed to the sound produced when two sheets of coarse sandpaper are moved against each other (louder).

In the knee joint friction, and hence mechanical vibration, is caused as the articular surfaces of the various bone structures impact upon each other. Primarily the area of most contact is found as the femoral condyles roll across the tibial menisci and from the patella articular cartilage as it glides in the trochlea grove. In a healthy knee the presence of intact articular cartilage mediates this friction to a large extent reducing the coefficient of friction and hence the level of sound produced. In contrast a knee joint affected by

osteoarthritis has surfaces roughened by degeneration of the articular cartilage, in extreme cases resulting in bone on bone grating. However the knee joint is a dynamic and complex system and acoustic theory shows that several other factors may affect the vibratory signal as it propagates through the joint (Howard and Angus, 2009).

2.31: Factors affecting signal intensity and propagation in the knee joint

Acoustic propagation of sound through any media tends to be reduced as it travels through it. Intensity of the sound decreases for every doubling of the distance travelled (Fletcher, 1992). Obviously at the relatively small distances that the acoustic signal propagates over in the knee joint even a relatively small increase in distance could thus be crucial in the reduction of signal intensity.

The generated vibration may also be further decreased as it reaches transition boundaries within the propagation medium, such as the vibratory signal moving through the synovial liquid of the joint encountering a bony structure, an example being the vibration signal produced by the action of the femoral condyles on the tibial plateau passing into the bone of the patella. This transition from propagation in a fluid medium to propagation through a solid one causes a decrease in the vibratory energy of the signal and thus results in a dampening effect (Gan, 2012). This is in part due to absorption of the signal energy as it enters the new medium but is also due to dissipation caused by refraction and reflection of the signal as it bounces off the surface interface.

The signal may also be focussed as it comes into contact with parabolic structures and sharp corners (Everest and Pohlmann, 2009). It can be theorised that such a scenario may occur in the knee as the vibration signal travels through a solid structure such as the patella, in this case the acoustic energy of the signal would then be focussed into the parabolic edges of the patella.
Such dampening and focussing of the signal can therefore result in marked differences of signal intensity found across the joint (figure 6).

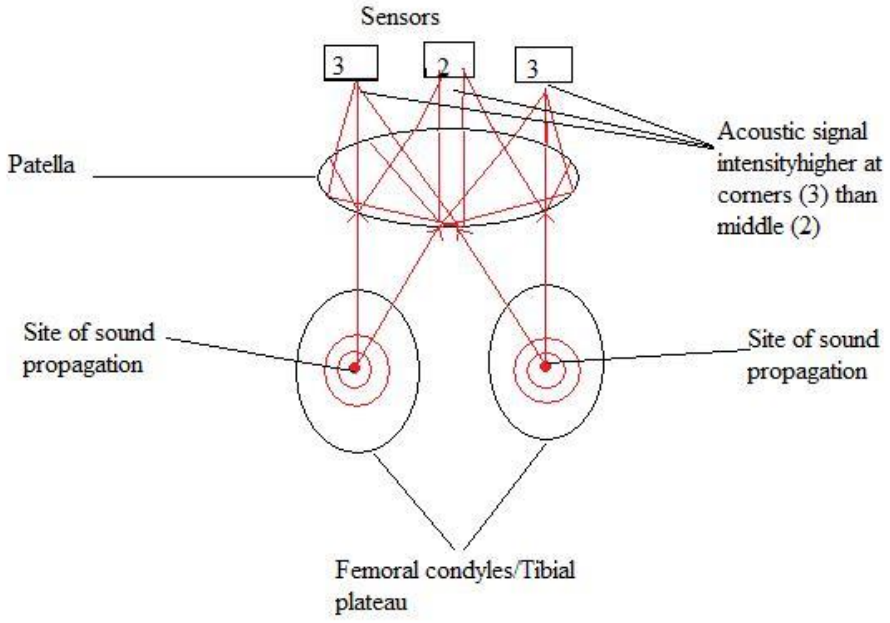

Figure 6. Acoustic signal propagation through the knee joint.

The viscosity of the fluid medium also will affect the propagation of the signal, however these effects are largely only felt over greater distances than those found in the knee joint and therefore play a much smaller role than the actual distance travelled by the vibration. Of note however that is a foam cellular or matrix type structure greatly dampens the intensity of sound (Britan et al., 2009). Once again it could be theorised that the presence of cartilage degeneration associated with osteoarthritis may result in the synovial fluid developing matrix like characteristic and dampening the vibration signal. The variability in the signal intensity that is introduced by such fluid/friction resistance effects as describe here are reproducible by the phonoarthrometer when generating a prediction corridor as the software is designed to account for this (for a detailed explanation of the software algorithm operation see section 3.4).

2.32: The effect of osteoarthritic change in the knee joint on vibratory signal intensity

As previously stated one would expect that the presence of osteoarthritic degeneration in the joint would result in a greater level of sound produced from the joint due to the increased level of friction from the roughened articular surfaces and in the case of severe

degeneration, bone on bone contact. At the origin of the vibration signal within the knee joint this may indeed be the case but this greater signal intensity may also be dampened by the presence of other factors attenuating the signal as it passes from the site of generation through the knee joint.
Firstly it is likely that the extra swelling and fluid associated with osteoarthritis due to inflammation of the tissues within the knee joint will increase the distance that the signal has to pass through the propagation medium, this increase in distance although small would have a significant effect in reducing vibratory signal intensity.

Secondly the increase in joint debris (loose cartilage and bony surface fragments) represents a significant increase in the number of boundary transitions that the signal has to pass through as it exits the joint. Each boundary transition will have the effect of dampening the signal as it is absorbed, reflected and refracted (Hayrapetyan et al., 2012).

Thirdly it can be theorised that increased joint debris may be acting in a similar way to a fluid filled matrix (or cellular foam) that greatly dampens the intensity of the signal as it travels through it. Increased pitting and erosion of bones surfaces may also create a sponge like effect on the bone surface (figure.7)

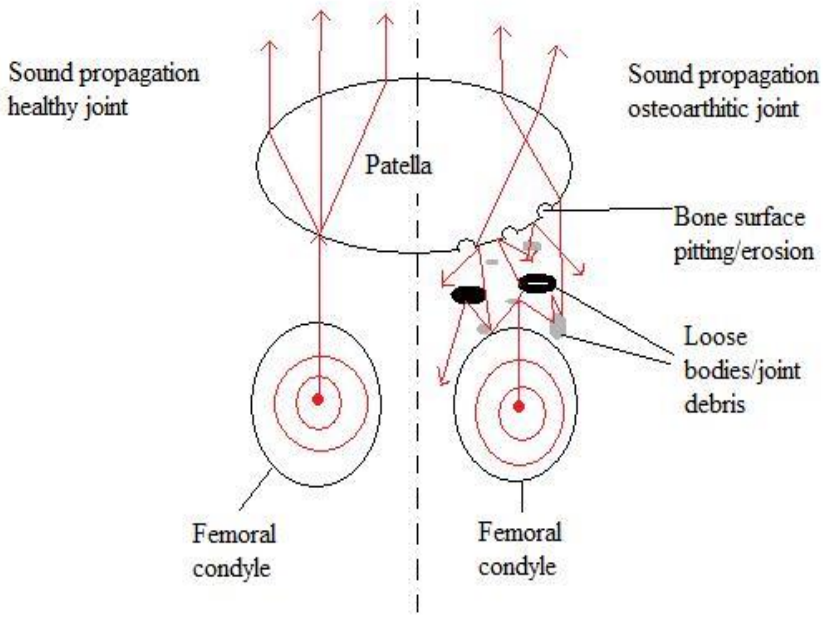

Figure 7. Acoustic propagation of sound in a healthy vs. an osteoarthritic knee joint.

2.4: Detecting and diagnosing osteoarthritis

Diagnosis of osteoarthritis can be made with a reasonable degree of certainty based purely on history and clinical examination. X-rays may be required to confirm the diagnosis (Zifchock et al., 2011) if this is the case then typical changes seen on X-rays include joint space narrowing, subchondral sclerosis (increased bone formation around the joint), subchondral cyst formation, and osteophytes. Normal X-rays may not correlate with the findings on physical examination or with the degree of pain suffered. Usually other imaging techniques are not necessary to clinically diagnose osteoarthritis (Magee, 2008) but may be called upon to add detail to the diagnosis and allow a more considered plan for any treatment.

An overview of the type of musculoskeletal examination used to diagnose osteoarthritis would likely follow the following format; the primary care clinician would ask what complaints (symptoms) are manifesting themselves, take a medical history, perform a physical examination (looking for signs), and obtain blood testing (largely for differential diagnosis to rule out other knee conditions), imaging studies (X-rays or MRI scans), and, if needed, other diagnostic investigations (arthroscopy) (Magee, 2008). The chief complaints of an osteoarthritis patient are usually fairly consistent and focussed. These include pain, stiffness, swelling, weakness, deformity, fatigue, and decreased range of motion (Saadat, Bolbos and Ries, 2010).

Joint pain is the most commonly reported complaint in osteoarthritis. Early in the course of osteoarthritis, the pain may be poorly localized, asymmetric, and episodic and especially manifests itself as an aching pain, in the affected joint. Osteoarthritis pain is usually localized to the involved joint, and is not associated with systemic symptoms. The severity and frequency of the pain increases as the disease progresses from an early stage to more advanced stages (Halpern, 2003).

Stiffness is also commonly present in the osteoarthritic joint. Stiffness is experienced early in the disease process, often found in the affected joints following activity or

resumption of activity after a period of inactivity. For this reason it usually occurs in the morning after sleeping, and joints are described to feel gel-like or "stuck." The stiffness usually lasts for 10-30 minutes and improves with activity, moist heat, or a hot shower or bath (Gilbert, 2003). As the disease progresses, pieces of degenerated cartilage may shed into the joint, producing loose bodies that may cause the joint to either lock or give way (Saadat, Bolbos and Ries, 2010).

Osteoarthritis is subject to the following predetermining factors that will be considered during diagnosis:

Age: the age of the patient is a high predetermining factor for primary osteoarthritis as it affects chiefly the elderly, an estimated 70-85% of people over 55 years of age show signs of radiographic (visible by X-ray) osteoarthritis most however are asymptomatic. Increasing age is not an absolute risk factor however as not every elderly person develops osteoarthritis (Arden, Arden and Hunter, 2008).

Weight**:** obesity is a strong factor in the onset of osteoarthritis. As weight increases more stress is transmitted to the weight bearing surfaces of the knee, these inevitably lead to an increased level of degeneration of the articular surface (Buchholz, 2009).

Sex: before the age of 50 men show a higher prevalence of osteoarthritis, but after the age of 50 the roles are reversed and women show a higher prevalence (Athanasou, 2001).

Activity level: Certain forms of exercise are widely believed to increase bone density (bone mass index) in specific areas of the body. Bone mass index can be increased up to 26 percent in some locations in the skeleton through physical exercise (Saadat, Bolbos and Ries, 2010). Strenuous, high-intensity, and repetitive exercise, both sport and occupational, has been associated with the development of osteoarthritis, although there appears to be no increased incidence of osteoarthritis with moderate exercise (Jenkinson et al., 2009).

Occupation: Work-related activities that involve heavy manual labour or repetitive weight bearing actions that put increased stress on the joints have been shown to be

correlated with increased rates of osteoarthritis of the hip, knee, and other joints. (Marshland and Kapoor, 2004).

Trauma: A prior history of trauma or surgery is an important risk factor in the development of osteoarthritis in a joint damaged by ligamentous instability or meniscal tear in the knee (Englund, 2010).

2.41 Physical examination

Physical examination serves to verify that the symptoms expressed by the patient arise from the joint and are not manifestations of a periarticular process such as bursitis, (inflammation of a bursa). In a complete physical examination, each joint is palpated for tenderness, warmth, effusion and crepitus. Observation of a patient's gait pattern is important particularly to detect pain on weight bearing and the effect of osteoarthritis on walking ability. Passive and active range of motion, as well as pain associated with both must be evaluated and documented (Dutton, 2008).

The gait of the affected individual may be impaired. Range of motion limitations can be caused by pain, loss of cartilage, malalignment of the joint, osteophytes, effusions, flexion contractures or muscle spasms. Flexion contracture (inability to extend the knee) affects standing and walking ability on level surfaces, while limitation of flexion tends to restrict sitting ability and ascending or descending stairs. Malalignments such as varus (bow legged) angulation of the limb due to loss of articular cartilage in the medial compartment of the knee and valgus (knock-kneed) angulation due to loss of articular cartilage in the lateral compartment of the knee commonly occur in osteoarthritis (Saadat, Bolbos and Ries, 2010).

Crepitus may be present in the affected joint. This is defined as an audible or palpable sensation of roughness, crunching or crackling over a joint throughout passive (when moved by the clinician) or active (moved by the patient) range of motion (Saadat, Bolbos and Ries, 2010). Crepitus is thought to be a result of intra-articular debris or irregularity of joint surfaces. The detection of crepitus in patellofemoral, tibial, or femoral condyles around the knee correlates well with degenerative findings in arthroscopy.

Muscle loss may be associated with osteoarthritic change in the joint. Atrophy proximal to the involved joints because of progressive weakness and disuse may be observed. The loss of supporting muscle may increase the joint osteoarthritis, which can lead to cartilage damage, especially in the weight-bearing joints. Quadriceps femoris atrophy is not uncommon in the presence of knee osteoarthritis and is likely to be related to a limp or avoidance of use of the limb during weight bearing activity as a result of arthritic pain (Saadat, Bolbos and Ries, 2010).

Swelling, inflammation, synovitis, and joint effusion may be present. Swelling and joint effusion are seen in more advanced stages of osteoarthritis (Arden, Arden and Hunter, 2008). Tenderness to palpation over the joint is common but may be mild or absent.

2.42: Plain film radiography (X-ray)

Once the physical examination is over the most likely course is for the clinician to order a radiological assessment of the affected joint, this will most likely be by X-ray (Gilbert, 2003). For example radiographs see figure 8.

X-rays create an image of bone, soft tissues, and calcium on a negative photographic plate. Changes in bone and cartilage that occur with osteoarthritis are usually easy to visualize on an X-ray (Saadat and Link, 2010).

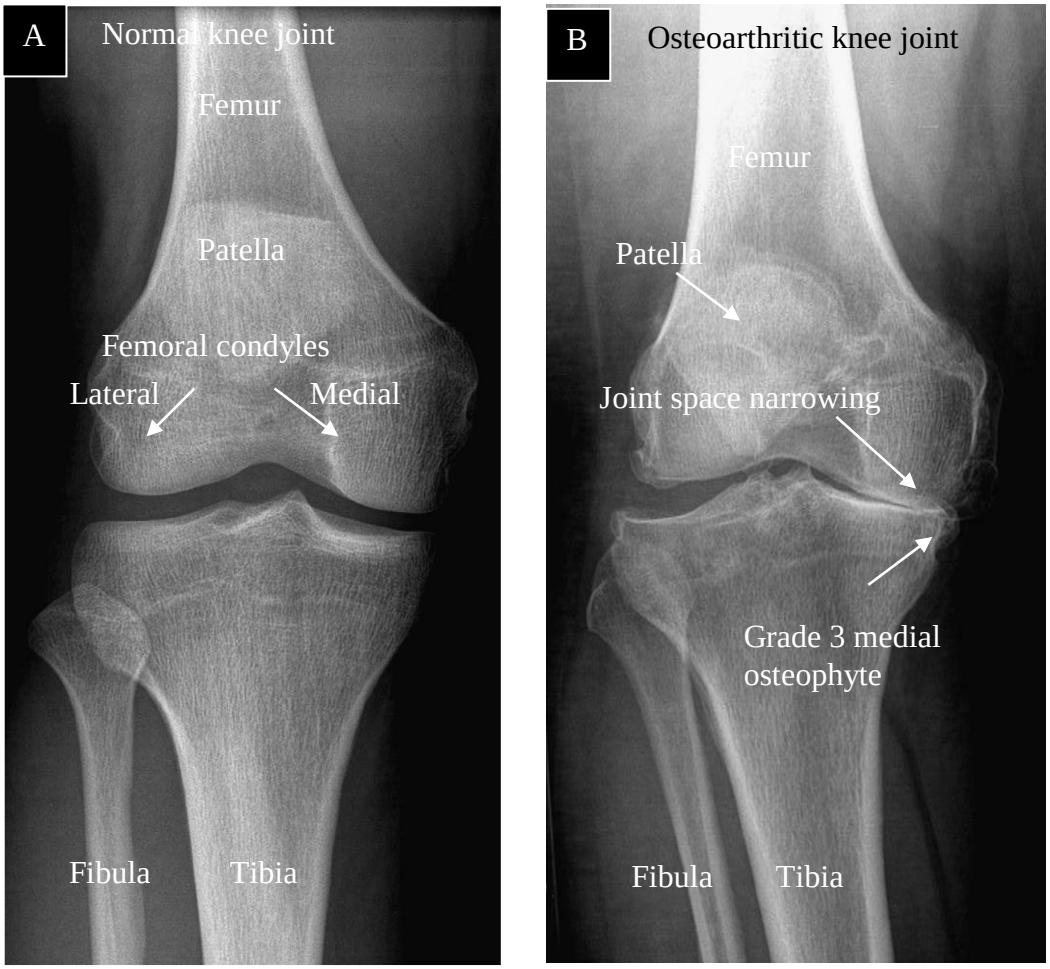

Figure 8. Plain film radiographs of normal (A) and osteoarthritic (B) knee joints. Adapted from Altman and Gold (2007).

Plain radiography is still the primary method for radiological diagnosis of osteoarthritis (Wilkinson, Carr and Doherty, 2005). Plain radiography is able to detect the principal pathological processes in osteoarthritis, such as the appearance of osteophytes, loss of cartilage thickness, as evidenced by development of joint space narrowing, as well as joint misalignment (Marijissen et al., 2008). However, gross changes such as these tend to appear in the later stages of the disease process. One of the most important drawbacks to x-radiography as a means of diagnosis is that it is insensitive to early changes in the cartilage and other articular tissues and to localised damage to the articular cartilage and its surrounding soft tissues. Despite its shortcomings, plain radiography is still the primary radiographic method for diagnosis of osteoarthritis and is the basis for the most widely used epidemiological grading system for osteoarthritis, the Kellgren-Lawrence scale (Kellgren and Lawrence, 1957).

Sometimes, contrasts or dyes are used along with plain X-rays to better define soft tissue structures. In a joint this is called an arthrogram. In view of the expense and greater radiation exposure of these procedures, their use has dramatically declined and they are now employed for special circumstances since magnetic resonance imaging (MRI) can provide a much more detailed assessment of the knee's internal structures.

For the radiographic diagnosis of knee osteoarthritis, the knee joint can be regarded as consisting of three compartments: medial femorotibial, lateral femorotibial and patellofemoral compartments. Osteoarthritis can cause pathological changes in all three compartments, although radiographic changes are usually present in only one or two of these (Saadat and Link, 2010)

In osteoarthritis, abnormalities in the patellofemoral compartment are commonly observed, usually combined with abnormalities in the femorotibial compartments. It is Rare to find abnormalities confined to the femorotibial compartments. The ability of the radiograph to allow detection of the pathologic abnormalities depends on the method of examination. Routinely techniques such as antero-posterior weight bearing and lateral radiographs are used. These are still limited in their sensitivity to delineate early alterations found in osteoarthritis (Saadat and Link, 2010) but some degree of joint space narrowing, sclerosis, cysts and osteophytes can usually be detected in the more involved weight-bearing medial or lateral femorotibial compartment. For this reason weight-bearing radiographs are often used to supplement the radiographic examination in these cases where early osteoarthritis is indicated by previous physical examination (Westbrook, 2008). These techniques provide a better assessment of cartilage loss as the joint space width decreases under the body weight. It also allows more accurate delineation of subluxation (incomplete or partial dislocation**)** of femur and tibia and of varus (bow-legged) and valgus (knock-kneed) angulations (Saadat and Link, 2010). Even with the addition of the weight-bearing radiographs to the routine examination, the degree of abnormality in the less-involved femorotibial compartment is difficult to determine, and it may be better judged by using Magnetic Resonance Imaging. Patellofemoral compartmental analysis requires special radiographic projections, including tangential and oblique views (Saadat and Link, 2010).

The progressive cartilage loss in osteoarthritis accounts for the fundamental radiographic change in osteoarthritis, joint space narrowing. The loss of joint space is usually restricted to the affected compartment. This cartilaginous destruction evidenced by loss of joint space is what differentiates osteoarthritis from other causes of joint pain, such as rheumatoid arthritis, which involves more diffuse abnormalities in cartilage. Extrusion of the meniscus, which may be observed in osteoarthritis, can also cause joint space narrowing detectable by radiography (Saadat and Link, 2010). Cartilage is not imaged directly using conventional radiographs, cartilage thickness can be estimated from the width of the joint space, assuming that the opposing joint surfaces are in contact, as is the case in standing. Since articular cartilage itself is not viewed, changes in the internal structure of cartilage such as localized ulceration, are not revealed, making this technique rather insensitive to localised pathological changes within the knee (Westbrook, 2008).

Changes in the thickness and biomechanical properties of articular cartilage in the evolution of osteoarthritis, lead to increased transmission of force to the underlying bone. The underlying bone responds initially with increasing local blood flow and bone production; however, this response is later overwhelmed and trabecular microfractures might ensue. These later changes manifest as subchondral sclerosis on radiographs (Buckland-Wright, 2004). Sclerotic bone is found consistently in compartments with articular space narrowing, and this feature is striking in areas of the joint denuded of hyaline cartilage. Sclerosis of subchondral bone is more frequent in the tibia or in both the femur and tibia; isolated sclerosis of the femur is unusual (Saadat and Link, 2010). Osteophytes are considered by many physicians to be the most characteristic abnormality of degenerative joint disease (Saadat and Link, 2010). Osteophytes develop in areas of joints subjected to low stress; they are considered to be a reparative response of the remaining cartilage, however there is evidence to suggest that osteophytes can arise from periosteal or synovial tissues as well. Radiographically, marginal osteophytes appear as variably sized lips of new bone around the edges of the joints on both femur and tibia. Central or interior osteophytes simulating intra-articular bodies may also be observed, especially on the femoral condyles. Marginal or central osteophytes contribute to intra-articular surface irregularity as well as sharpening of the tibial spines. It should be noted that although the presence of osteophytes combined with articular space narrowing is usually considered a manifestation of osteoarthritis of the knee, the relationship of osteophytes to the articular disease is subject to debate. It might be that the inclusion of

compartments with osteophyte formation and no other finding, accounts for a high frequency of tricompartmental involvement in some reported series of patients with osteoarthritis of the knee (Saadat and Link, 2010).

There is an increasing acceptance that osteoarthritis may not represent a single disorder but that it is a disease spectrum with a series of subsets that lead to similar clinical and pathological alterations. As a result, many groups have developed specific criteria relating to the differing pathological processes of osteoarthritis in specific joint sites.

The radiographic features currently used to assess osteoarthritis were originally selected to measure various aspects of cartilage loss and subchondral bone reaction. Although several radiographic grading systems have been proposed over the last 20 years, and several radiographic atlases have been developed to aid in the interpretation of radiographic findings (Nagaosa et al., 2000) (Altman and Gold, 2007), the method developed by Kellgren and Lawrence (1957) was adopted by the World Health Organization in Rome, in 1961, as the accepted standard for assessment of osteoarthritic degeneration (Teichtahl et al., 2008). This system assigns one of five grades (0 to 4) to osteoarthritis at various joint sites. The criteria for increasing severity relate closely to the sequential appearance of osteophytes, joint space loss, subchondral sclerosis and cyst formation. The grading system is outlined in table 1. The Kellgren and Lawrence grading system has been criticized for its reliance on the presence of the osteophytes for classification of disease. The time sequence of when bony changes occur and articular cartilage is lost is still controversial. Thus, according to Kellgren and Lawrence, presence of a narrowed, sclerotic joint with deformity cannot be classified as osteoarthritic unless an osteophyte is also present. There also remains the problem of how to classify the individuals with grade 1, doubtful osteophytes (Saadat and Link, 2010).

Table 1. The Kellgren-Lawrence grading system for osteoarthritis.

Grade	Criteria
0	Normal
I	Doubtful narrowing of joint space, possible osteophyte development
II	Definite osteophytes, absent or questionable narrowing of joint space
III	Moderate osteophytes, definite narrowing, some sclerosis, possible joint deformity
IV	Large osteophytes, marked narrowing, severe sclerosis, definite joint deformity

Adapted from Kellgren and Lawrence (1957).

2.43: Magnetic resonance imaging (MRI).

Plain radiography of the knee is currently the most commonly used technique for radiographic diagnosis of knee osteoarthritis; however this technique has several limitations. Early and focal changes in the cartilage and other articular tissues are not directly visible when using radiographs for a diagnostic confirmation, (Ding, Cicuttini and Jones, 2007). Cartilage loss can only be indirectly inferred by the development of joint-space narrowing when using X-rays (Saadat, Link and Ma, 2010).

Because of the focal nature of the disease process, prominent articular changes are often readily apparent in one or two compartments of the joint and absent or mild in other compartments, despite pathological abnormalities in those compartments (Saadat, Link and Ma, 2010). Apart from direct observation by invasive arthroscopy Magnetic Resonance Imaging (MRI) of the knee is currently the most successful technique for the imaging of cartilage and articular structures within the knee joint (Peterfy et al., 2006). MRI offers superior soft tissue contrast, is capable of non-invasive evaluation of cartilage morphology as well as function, and does not use ionising radiation (Saadat, Link and Ma, 2010).

A variety of different pulse sequences can be used in the MRI of cartilage, each technique takes advantage of the different contrast characteristics of articular cartilage and the soft tissue found adjacent. The main two pulse sequences currently employed for knee imaging are T 1-weighted Spoiled Gradient Echo (SPGR) and T 2-weighted Fast Spin-Echo (FSE). Visible distinction between cartilage and subchondral bone, is provided by T 1-weighted imaging. Contrast between cartilage and synovial fluid using T 1-weighted imaging is however not so useful (Saadat, Link and Ma, 2010). T 1-weighted imaging allows the building of 3D images in a relatively fast timescale (Westbrook, 2008) In order to image cartilage, fat-suppressed T 2-weighted Fast Spin-Echo (FSE) is particularly valuable as it yields good contrast with the synovial fluid at the cartilage surface, permitting identification of cartilage surface lesions (Saadat, Link and Ma, 2010). Most significantly, FSE imaging sequences are also valuable for examination of other intra-articular structures, such as ligaments, menisci and subchondral bone (Saadat, Link and Ma, 2010) the offset to this is the relatively long scan time and the possibility of artefacts caused by patient motion during that time (Westbrook and Kaut, 1993).

In general, hyaline, the typical MR protocol for evaluation of articular cartilage will include proton density, T 1, T 2 and fat-suppressed images with fast spin-echo-based techniques such as Fast Spin-Echo (FSE). These will give a comprehensive picture of the morphological changes associated with injury and subsequent degenerative processes associated with osteoarthritis (Westbrook, 2008). Images are commonly acquired in all three planes (Peterfy, Schneider and Nevitt, 2008). Further images may be required for the detailed evaluation of the posterior patellar cartilage and central portion of the femoral condyles and tibial plateau.

Using MRI the beginnings of degenerative disease may be seen as early alterations in cartilage contour morphology (fibrillation, surface irregularity), changes in the thickness of cartilage or changes in the signal intensity of the cartilage (Conaghan et al., 2006). These may be attributed to pre-morphological cartilage damage manifesting itself as collagen degradation and increased water content of cartilage (Saadat, Link and Ma, 2010). Well-established lesions typically represent as multiple areas of cartilage thinning of various depths and sizes and are usually found on the opposing articulating surfaces. Early indications of cartilage damage may however be represented by a thickening of the

articular cartilage, as like other connective tissues, it swells when injured. This may represent an early manifestation of osteoarthritis in humans (Saadat, Link and Ma, 2010)

Along with these Changes within the articular cartilage, there is a simultaneous rebuttressing and sclerosis of the underlying cancellous bone (Buckland-Wright, 2009). MR imaging can also visualise alterations within the subchondral marrow, this is commonly referred to as "bone bruise" or "bone marrow oedema". Bone marrow oedemic lesions on MRI are strongly associated with the presence of pain in knee osteoarthritis (Felson et al., 2003**)**.

Because of its excellent contrast resolution, high spatial resolution, and the multiplanar capabilities, MR imaging is an excellent method for assessment of articular cartilage (Saadat, Link and Ma, 2010). In practice, however, the clinical usefulness of this technique in providing information regarding the integrity of the articular cartilage is uncertain. As with any non-direct medical imaging, MRI does have its limitations.

Most importantly all MRI images include some degree of artefact, often it is possible to compensate for these. The main source of artefact in MRI of the knee is due to pulsation of the popliteal blood vessel or movement by the patient (Westbrook, 2008). In this case phase mismapping can be produced by the anatomy moving along a gradient during the MRI pulse sequence. Any structure that moves during the imaging process can produce this and cause an artefact known as 'ghosting' (Westbrook and Kaut, 1993).

Of note is the advances made in dynamic imaging using MRI. Using small bore magnets designed specifically for orthopaedic imaging real time kinematical imaging of the knee joint can be achieved (Westbrook, 2008). The main use to date with regards to osteoarthritic knees is within studies aimed at determining the motion of the osteoarthritic joint in an attempt to further aid efforts to reproduce normal knee kinematics in the prosthetic knee (Scarvell et al., 2007).

A second important limitation is one with considerations of the patient in mind.
The strong magnetic fields employed in the use of MRI contraindicate the use of this imaging process with regards to pacemakers, aneurysm clips, ferrous intra-ocular foreign bodies, cochlear or spinal implants (Westbrook, 2008).

The percentage of the population fitted with pacemakers is of greater significance when viewed as a percentage of the population of over fifty five years of age, a strong determinant of osteoarthritic susceptibility.

Patients with metal prosthetics implanted, for instance hip or knee replacements are not contraindicated as such, but may experience a degree of discomfort (Westbrook, 2008).

2.44: Arthroscopy.

Arthroscopic evaluation of the internal knee structures is a minimally invasive surgical procedure performed under anaesthesia in which small (arthro) scopes are inserted into the knee joint in order to directly visualize the articular surfaces on a monitor screen (Saadat, Link and Ma, 2010).
Arthroscopy is rarely used these days as a diagnostic tool; it is more likely that it will be used as a therapeutic intervention on a knee already clinically diagnosed as osteoarthritic (Felson, 2010) and that a confirmed diagnosis will be a secondary consideration (Halpern, 2003).

To illustrate this point, several recent NHS recommendations, found online (Suffolk NHS, 2011; West Essex NHS, 2009), show a marked attempt at limiting the use of arthroscopic investigation for the sole purpose of diagnosis and in all cases recommend that MRI investigation is seen as the primary method of diagnosis where osteoarthritis has not been able to be determined by X-ray.

However when all else fails arthroscopy can reveal the joint structure, as no other form of medical imaging, by direct observation. Direct visualization through arthroscopy is more sensitive and specific than plain radiography or MRI in detecting cartilage lesions Arthroscopy is able to provide a direct, magnified view of all six articular surfaces of the knee. (Saadat, Link and Ma, 2010).

Its major drawback, although deemed minimally invasive, is the surgical nature of the procedure, and the need for some form of anaesthetic. Also of consideration is the fact that although it gives unprecedented visualization of the articular cartilage surface, it is not well suited to assessment of cartilage thickness or the depth of any lesions present.

Articular cartilage lesions can be defined by three baseline parameters: depth, size and location. The most widely used scoring system is the "Outerbridge" system presented below (table 2).

Table 2. The Outerbridge scoring system.

Grade	Criteria
0	Normal
1	Articular cartilage softening and swelling
2	Fragmentation and fissuring in an area less than 12 mm (half inch) diameter
3	Fragmentation and fissuring in an area more than 12 mm (half inch) diameter
4	Erosion of cartilage to subchondral bone

Adapted from Saadat, Link and Ma, 2010

2.5: Conclusions

An examination of the knee joint shows a complex dynamically interacting structure. Bones, cartilage and ligaments all show a complex inter-relation with one another to function as a stable, weight bearing joint, able to absorb shock and move smoothly.

Osteoarthritis is a poorly defined term that attempts to encompass the progressive degenerative changes found over time within the joints, "degenerative joint disease" is the best general phrase to describe degenerative processes in any type of articulation, with "osteoarthritis" being reserved for degenerative disease of synovial joints.

Osteoarthritis results from degeneration of the articular cartilage in the synovial joints this is characterized by development of fissures, cracks, and general thinning of joint cartilage, increasing thickness and sclerosis of the subchondral bony plate, outgrowths of osteophytes at the joint margin. Mild synovitis may also be experienced in the course of the disease.

Symptomatic progression of the disease occurs when the cartilage decreases in size or volume. Without cartilage or with less cartilage, bones lose their shock-absorbing buffers and begin to rub against each other. In Osteoarthritis of the knee, joint pain develops usually during weight bearing exercise due to the cartilage and meniscal degeneration, as these structures can no longer provide adequate shock absorption.

Difficulty in relating the complexity of the knee joint to the poorly defined causes and manifestation of osteoarthritis, leads to problems encountered by clinicians attempting a diagnosis. In most cases however a confident diagnosis can be based upon patient history and physical examination, with other forms of joint disorders being discounted along the way.

However to give a conclusive diagnosis the standard process is to provide some forms of medical imaging of the joint. This is usually by X-ray or MRI. Both techniques have validity regarding the types of tissue imaged for use by the clinician, and both have drawbacks regarding patient safety, cost and time taken to image the joint.

Importantly both methods are subjective in their evaluation of the joint, requiring a highly trained and experienced clinician to interpret the resultant images; several methods of evaluation based on scoring systems are found, with attempts at improved accuracy of these diagnostic methods being widely reported within the literature.

As a final summation, the literature presented suggests that efforts to produce a clinically evaluated objective method of diagnosing joint disorders has as of yet been unsuccessful. There is therefore a strong argument within the medical community for the development of a device that can give a purely objective diagnosis.
If this is to be via the usage of the joint acoustic signal then the internal noise generation mechanisms of the joint must be considered and from these it can be hypothesised from the stated mechanisms of noise generation found in the knee joint that:

1) Different points on the joint surface will produce differences in the acoustic signal intensity due to the signal being altered as in passes through different combinations of structural impedances in its pathway from the site of vibration generation to the signal collecting sensor.

2) Osteoarthritic affected knee joints will produce a vibration signal of different intensity to a healthy joint due to the differences in the quality of the joints' articular surface. The vibration signal intensity may then be further modified by various dampening and/or focussing effects caused by further factors (such as inflammation of the joint) associated with osteoarthritis as the signal travels through the joint.

3) Vibration signals produced by osteoarthritis at different locations within the knee joint will differ due to the transmission pathway from site of generation to the surface being different.

4) The alteration of the vibration signal in an osteoarthritic knee joint will be variable dependent on the stage of advancement of the disease, as the level of articular degeneration and dampening/focussing effects found within the knee joint will increase with the severity of the osteoarthritic change.

Chapter 3

Research methodology

3.1: Overview of the research

The phonoarthrometer has strong potential as a useful diagnostic tool. However, it is currently still at an early prototype stage, and has as of yet been largely tested on healthy knees in order to provide a baseline dataset of normal (never injured and free of pain) knees. This study is therefore scientifically justified in that to prove/disprove its clinical usefulness, it must be tested on damaged (in this case osteoarthritic) knee joints and provide convincing results of an ability to detect osteoarthritis across a number of individuals, this in itself must then be evaluated when compared to standard detection means.

This evaluation involved taking the device into a clinical setting and collecting data from participants with clinically diagnosed osteoarthritis and using this data to provide a view of what the phonoarthrometer can detect with regards to knee osteoarthritis. This can then be used to assess any proposed clinical usage for the device. Data was concurrently gathered from healthy knee joints in order to build the core database of joint angular micromotion types that the device uses in order to produce the final diagnostic output charts and to provide a control group for statistical comparison with the collected osteoarthritic data. . This is explained further in section 3.31.

3.11: Aims and objectives.

The aim of this study can be broadly described as to test whether the prototype phonoarthrometer has the ability to detect osteoarthritis in the human knee joint. In order to do this a number of testable hypotheses derived from the literature review presented in chapter 2 would seem to provide a good starting point for the development of specific aims and objectives designed with this in mind.

1. Firstly the study aims to test the hypothesis that transposing the sensors used in the collection of the vibration signal to differing points on the surface of the knee joint will modify the received signal due to the different transmission pathways

that the vibration signal takes through the knee. This experimental testing has as of yet not been undertaken and as such represents an important gap in the knowledge relating to this field of research.

2. Secondly the study aims to test the hypothesis that the presence of osteoarthritic change within the knee joint will have an effect on the vibration signal generated in the knee. If such an effect is present the vibration response collected at the surface of the knee should be comparably different to a normal knee vibration response.

If this second hypothesis proves true and such an effect can be observed it should therefore be possible to test two further hypothesises:

3. Firstly the hypothesis that difference in the transmission pathway of the generated vibration signal from osteoarthritic knees may allow the location of the osteoarthritis within the joint to be deduced, due to observable differences in the collected vibration response. It may therefore be possible to differentiate medial compartment from lateral compartment osteoarthritis.
4. Secondly the hypothesis that the grade of severity of osteoarthritis within the knee joint may affect the transmission pathway of the vibration response through the knee in such a way that differences in the collected vibration response will be observable.

The research has a number of objectives:

1) Normal vibration responses from healthy knee joints must be collected for the purpose of building the microstructure library, a database of vibration responses linked to attributes derived from the angular velocity of the knee joint. This in effect can be considered as a training phase for the phonoarthrometer software.
2) A larger group of healthy normal knee vibration responses needed to be collected in order to provide a control group against which the osteoarthritic affected group can be assessed.
3) Within this group of healthy normal knees a smaller subset were asked to perform an extended version of the data collection protocol, this involved

placement of the accelerometer sensors at differing points around the knee in order to test hypothesis 1.

4) A group of vibration responses taken from clinically diagnosed osteoarthritic knee joints were collected. These were then assessed in comparison to the results from the normal group; in order to test hypothesises 2, 3 and 4.

3.12: Research design and theoretical framework.

The primary objective of the research is to build on the previous work done in building the prototype and to clinically evaluate its ability to detect osteoarthritis. Assessment of the devices' ability was based on use of the final statistical output files produced by analysis of the collected vibration responses and to a lesser degree by visual observation of trends in the output charts produced. Secondary considerations were dependent on this primary outcome, should the device be successful in detecting osteoarthritis the secondary considerations will be: to what degree can the device detect osteoarthritis and how does this detection compare to conventional methods (MRI scans/arthroscopy). If the device is unsuccessful then consideration was given to why the phonoarthrometer failed to detect osteoarthritis, what the limitations of the device are and what can be done to improve the detection ability.

The study focuses on the human knee joint. Firstly and primarily, given that the purpose of this research is to evaluate the performance of the prototype device rather than redesign it, the knee is the joint on which the phonoarthrometer was focussed during its development and with which it is currently calibrated to work (Abbott, 2008).

The choice of the knee joint during the development of the prototype phonoarthrometer was a considered one; historically almost all work has been done using the knee as the joint under investigation. Of the 76 papers identified in this area of research only a few are concerned with joints (the shoulder, hip and temporomandibular joints) other than the knee, these are often related to specific application of techniques that are at this time not be transferable to the knee. Therefore in order to give a credible comparison of the findings from study in relation to the findings of previous literature the knee joint was selected.

A further consideration is a practical one the knee is a large and relatively easily accessed joint, this makes participant involvement easier as they are only required to wear shorts for the data collection and it is easily palpated with orthopaedically recognised surface anatomical landmarks for the attachment of the sensors.

The study is also focussed on osteoarthritis in the knee joint. Osteoarthritis is one of the most common joint disorders and the knee is the commonest large joint affected by osteoarthritis (Dickinson and Hosie, 2003). If proven, the ability of the phonoarthrometer to detect osteoarthritis would be of high clinical significance as current means of detection are relatively costly, frequently require long waiting times and can in some circumstances be invasive procedures.

In addition, highly promising results were obtained from osteoarthritis of the knee by the phonoarthrometer in the limited case study work carried out in Abbott (2008). This work gives a tentative starting point for further investigation, these case studies suggest that osteoarthritis can be detected by the device but further testing on a greater number of individuals is needed with a more robust evaluation of the phonoarthrometers' ability.

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3.2: Method.

3.21: Equipment.

The hardware used for the recording of the raw data comprises a number of sensors and recording devices supplied by Biometrics Ltd. These sensors are the same as used in the original development of the phonoarthrometer (Abbott, 2008).

The use of these sensors conformed to the manufacturers recommendations. Eight recording channels are available in total. Each accelerometer (model: ACL300) uses three channels, recording vibrations along an X, Y, and Z axis within the knee joint, the electro-goniometer (model:SG150) can be used to record angular motion in either one or two channels each channel corresponding to changes angle for either the sagittal plane or the rotational plane of the knee.

It was decided that for this study the arrangement of sensors used would be modified slightly from the original configuration as used by Abbott (2008). The original configuration of one accelerometer placed on the patella and one electro-goniometer would be retained as this would enable any data gathered from these channels to be comparable to the developmental work. In addition to this a second accelerometer would be added, placed on the medial joint line of the knee, allowing a second point of reference from which to gather the vibration signal from the knee joint in order to test hypothesis 3. Finally as the electro-goniometer now recorded in two planes both data channels would be recorded.

The reasoning behind these modifications is that the previous developmental study (Abbott, 2008) used a configuration of one accelerometer placed on the patella, one electro-goniometer (connected by one channel recording the angular motion of the knee's movement in the sagittal plane only) and four electromyography (EMG) sensors to record the raw data. The original configuration for the device used the EMG sensors to record electrical activity within the muscles surrounding the knee joint. The results from the data collected by Abbott (2008), whilst illuminating, did not go far enough to providing definitive evidence of the proposed link between motor unit firing frequencies and microscale motion, despite it seeming extremely likely that they were linked. It is not the intention of this PhD research to provide evidence for this link and the additional work

required to provide the evidence for this link would be well beyond the scope of this PhD. Since continuing with the use of these EMGs would only provide further data that could not be fully utilised or interpreted by the phonoarthrometer at this time, it was decided that replacing them with a second accelerometer placed at the medial joint line would provide more useful data in relation to what was occurring within the knee joint, permitting the testing of hypothesis 3.

Therefore the configuration of sensors used for this study is as follows:

- One accelerometer placed in the centre of the patella as used in Abbott (2008)
- One accelerometer placed on the medial joint line and in line with the medial femoral condyle.
- An electro-goniometer (recording the knees angular movement in both the sagittal and rotation plane) connected to the eight channels available.

Attachment of the patella and medial joint line accelerometers and the electro-goniometer to participants' knee joint is shown in figure 9.

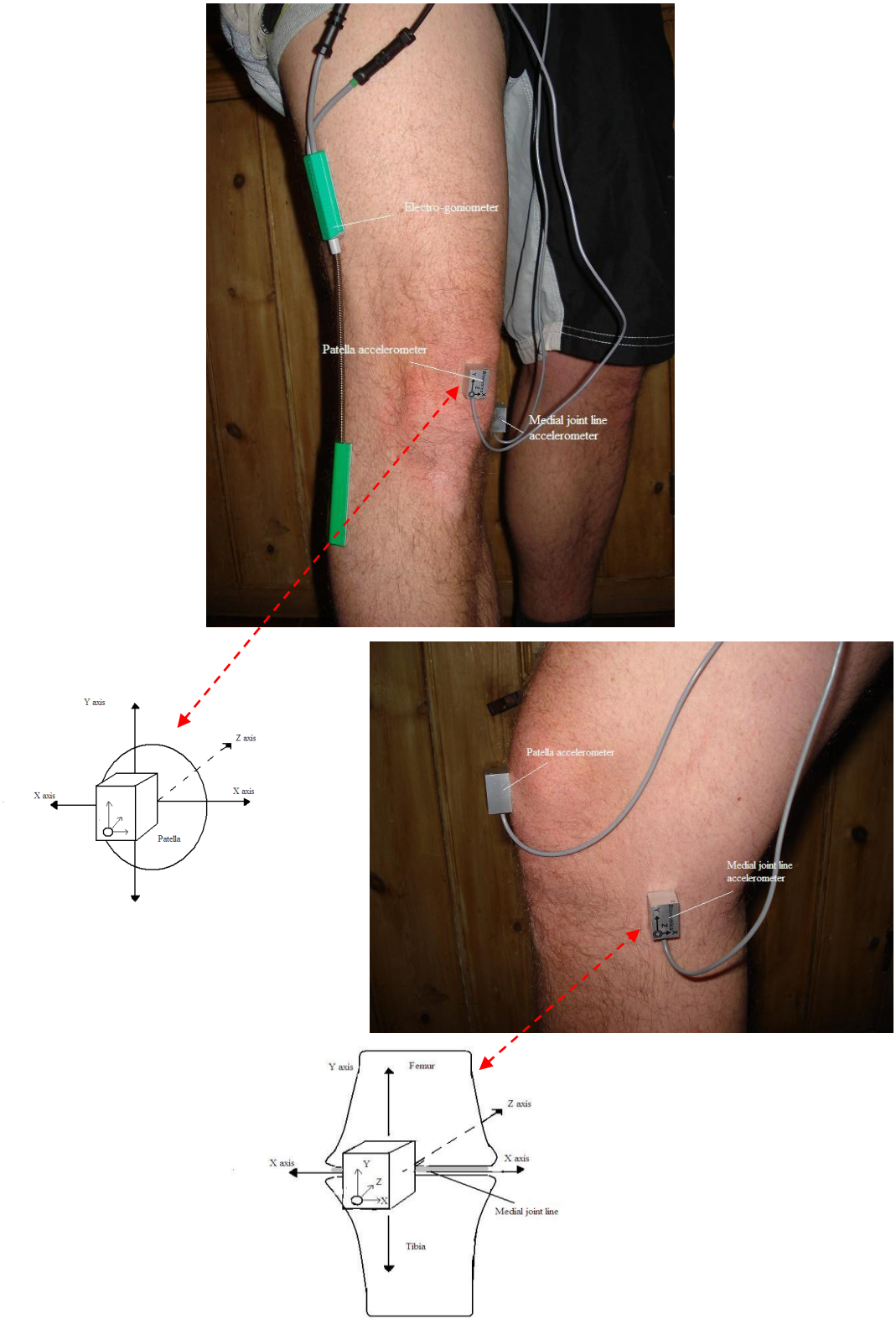


Figure 9. Attachment of patella and medial joint line accelerometers (with axial recording directions) and the electro-goniometer to the knee (Authors photographs).

It was envisaged that the placement of this second accelerometer on the medial joint line would provide a secondary reference point in relation to the patella accelerometer and that by careful interpretation of the resultant statistical output and output charts further information might be deduced about the affected location of the osteoarthritic change within the joint, for instance, whether osteoarthritis in the lateral tibiofemoral compartment could be distinguished from osteoarthritis in the medial tibiofemoral compartment.

A major difference to the equipment was that it could now be termed wireless as the original connecting wire between the sensors and the laptop had been replaced with a wireless capability. This is a crucial development, as it greatly increased the movement allowed to the participant, as they were now free of the connecting tether to the laptop. As a wireless system the participant could now perform a variety of motions previously not included in the protocol as used by Abbott (2008). This manifests itself as the inclusion of a walking test for the first time (see below for a more detailed description of the protocol) and allowed greater freedom when gathering and testing data from a weight bearing (loaded) knee joint.

It is also worth noting that the electro-goniometer will be connected by both its channels. The main angular motion of the joint is in the flexion extension plane; in the development research for the phonoarthrometer the electro-goniometer was only connected by one channel, the other being taken up by one of the now-redundant EMGs (Abbott 2008). However, the electro-goniometer supplied can record angular changes in the axial plane as well and this motion is of particular importance with regards to the screw home mechanism. It was decided that although the analysis of this data is currently beyond the processing capabilities of the current version of the phonoarthrometer software, the second electro-goniometer channel would be connected to gather this rotational angular data but that at this time the analysis of the data would be beyond the scope of the current study.

The positioning of the electro-goniometer follows the method as defined in the documentation supplied by biometrics. Figure 10 below gives an outline:

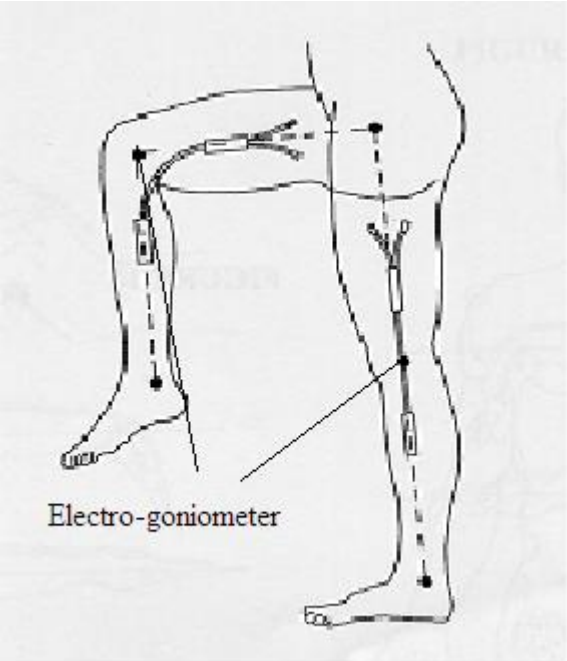


Figure 10. Attachment of the electro-goniometer, adapted from biometrics ltd.

In order to attach the electro-goniometer the subject was asked to stand in a neutral position with the foot flat to the ground. The distal end block is mounted to coincide with the sagittal plane and the leg is fully extended, the proximal end block is then mounted on to the thigh and once again aligned with the sagittal plane. The sagittal plane is found by asking the participant to manually locate the greater trocanter of the femur and the researcher manually locating the lateral femoral condyle, a line between the two indicates the sagittal plane. Both the greater trocanter and femoral condyle are accepted anatomical landmarks used by orthopaedic practitioners and are easily palpated.

The positioning of the first accelerometer corresponds to the location as defined in the previous development of the phonoarthrometer. By palpation the patella is identified and the accelerometer is positioned in the centre of the patella.

The second accelerometer is positioned on the medial joint line found between the medial tibial plateau and the medial femoral condyle; both these positions are recognised orthopaedic landmarks and are easily found by palpation (Dutton, 2008).

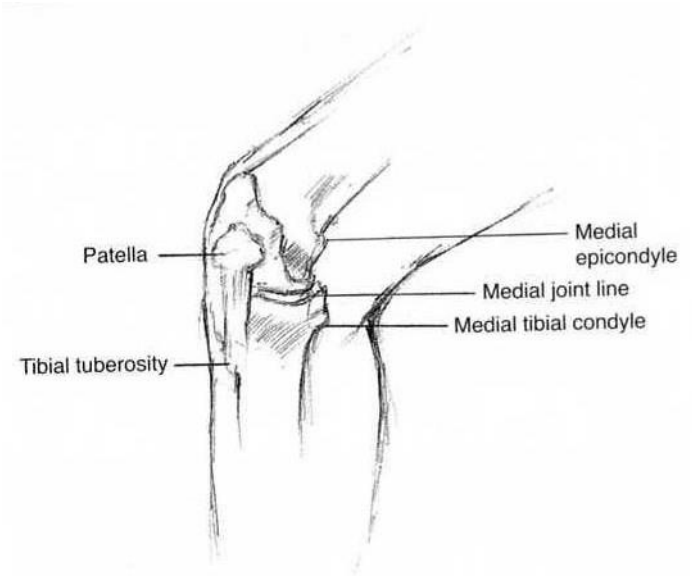


Figure 11. Palpable structures on the anteromedial surface of the knee, from Dutton (2008).

As mentioned previously the accelerometers are tri-axial and record vibration responses for X, Y and Z axes, these are marked on the accelerometers and denote the orientation of the axes. For the patella accelerometer the X axis represents the side to side vibration response, the Y axis vibration in the direction of movement and the Z axis vibration perpendicular to the patella. In the accelerometer placed on the medial line the X axis represents vibration forward and backward, the Y axis up and down and the Z axis is once again perpendicular to the joint although in this case to the medial line (see figure 9 for diagrammatic representation).

However this does beg the question as to what limitations on the accuracy of data recorded is placed on the correct orientation of the accelerometers. For instance to what degree is the data changed by variation in the positioning accuracy of the accelerometers and what impact will this have on the final output by the device.

In order to test these limitations a specific study was devised in which the sensors were placed at various points around the defined attachment locations. Due to the variation in participants' body size and shape these points were allocated as percentage of distances between locatable points. Participants from the normal healthy knee group were used for this purpose. 5 participants were used and the variable attachment points were as follows:

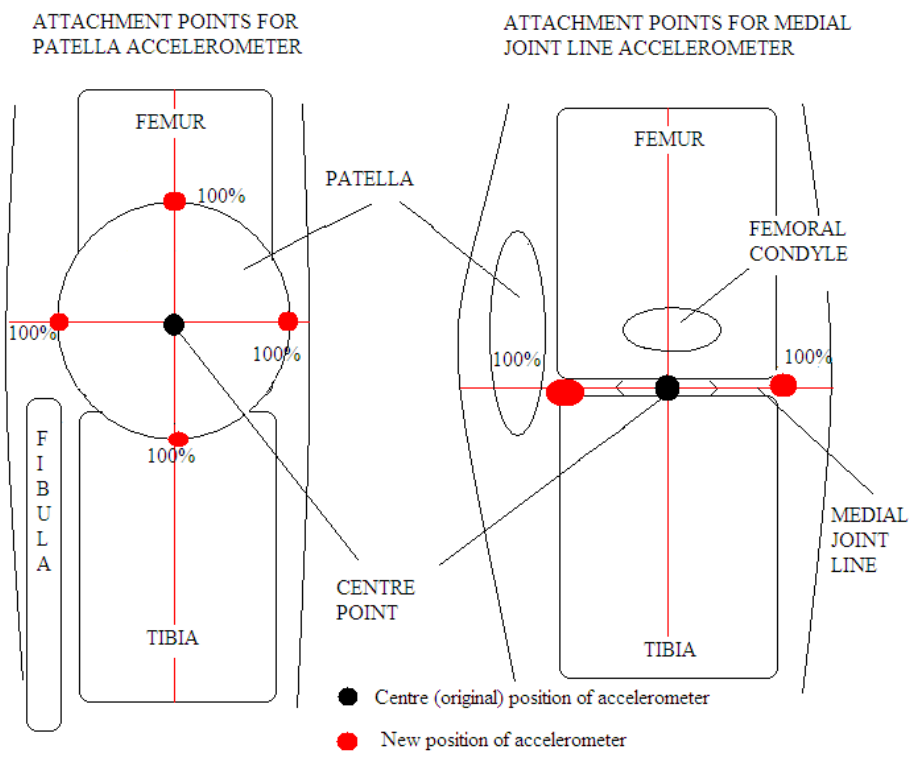
The patella accelerometer:

- Placed in an attachment location at a distance of 50% between the centre and the medial/ lateral edge.
- Placed in an attachment location at a distance of 50% between the centre and the proximal/distal edge.
- Placed in an attachment location at the medial/ lateral/proximal/distal edge.
- Placed in an attachment location above and below the centre of the patella on the distal femur and proximal tibia in order to give an indication of the extremes of the limits.

The medial joint space accelerometer:

- Placed in a attachment location at a distance of 50% between the sagittal plane and the coronal plane
- For extremes of limits placed in an attachment location on the medial femoral condyle, above the medial femoral condyle in line with a circumferential line drawn from the top and bottom of the patella respectively and below the medial tibial tuberosity.

Figure 12 gives schematic representation of the placement of the patella and medial joint line accelerometers at various positions on the knee.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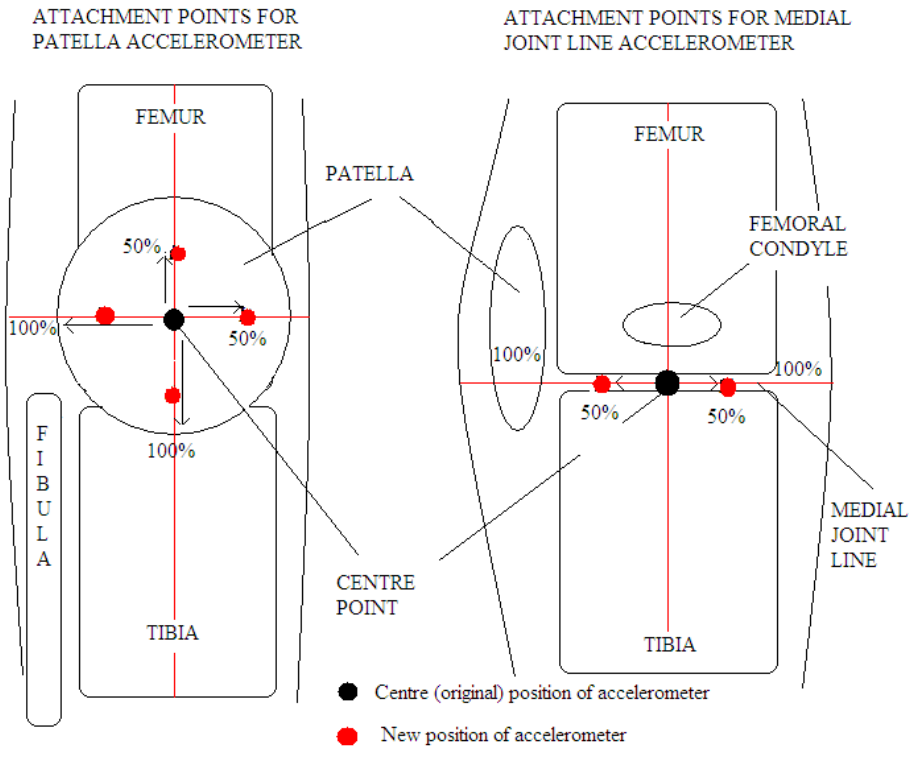
TIBIA
CENTRE POINT
FEMUR
FEMORAL CONDYLE
100%
100%
MEDIAL JOINT LINE
TIBIA
Centre (original) position of accelerometer
New position of accelerometer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TIBIA
Centre (original) position of accelerometer
New position of accelerometer

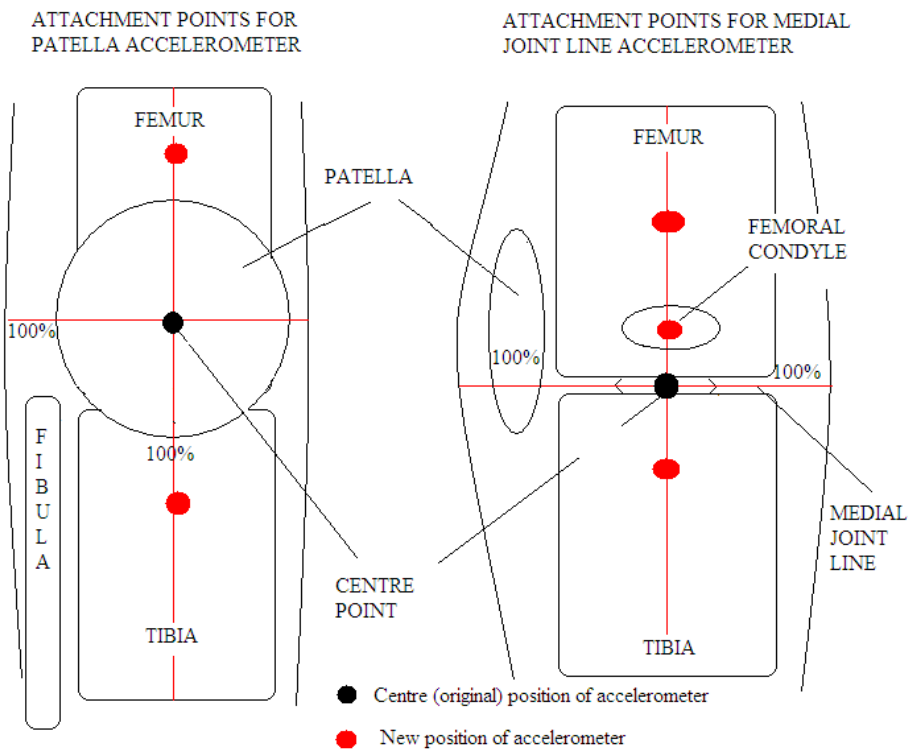


Figure 12. Schematic representation showing attachment points for the patella and medial joint line accelerometers in testing the accuracy of sensor placement.

3.3: Data collection.

Data was collected from distinct groups of participants, namely participants from the Basildon hospital based part of the project with clinically suspected osteoarthritis of the knee and from a group of participants with healthy knees from staff and students of Anglia Ruskin University labelled as ‘normal’ for the purpose of constructing the core training database utilised by the system and as a control group. The classification of ‘normal’ was defined for this purpose as being free of pain at the time of testing and having no lower body injury or past history of lower body injury that required medical treatment by a clinician.

The participants were asked to fill out a questionnaire in order to confirm the normal/healthy or osteoarthritic status of their knee and to supply various further information that would be of use in the study.

The first part of this questionnaire asked primarily whether their knee was free from pain at that particular time, pain experienced within the joint is a strong indicator for joint problems. They were asked about any previous injuries or surgery to the lower body. The entire lower body (from waist downwards) was considered here as any previous damage or disease could be influential in changing the way that the knee joint behaves and thus would discount the knee from being defined as "normal". With consent and where possible participants were asked to supply details relating to injuries or surgery undergone. This first part of the questionnaire was therefore of vital importance as it was used to assess the knee given the following inclusion/exclusion criteria:

- For the group with suspected osteoarthritis, the inclusion criteria were that the participants were suspected of or diagnosed as having osteoarthritis of the knee joint by a trained clinician. The participants were all over eighteen years of age and able to give informed consent under their own judgment.
- For the group of normal knee joint individuals, the inclusion criteria were that they had no history of serious injury (requiring medical attention) to the lower body (waist down), and were free of knee joint pain at the time of examination. The participants were all over eighteen years of age and able to provide informed consent.

It should be noted that the previous development of the phonoarthrometer (Abbott, 2008) used a database gathered from 14-20 year olds; however it also showed that normal participants over the age of eighteen could be detected as normal by the device. However only one individual was tested as a normal at an age above twenty years by Abbott (2008), and this study by including individuals from a broad range of age groups sought to confirm that the phonoarthrometer has the diagnostic potential to characterise a knee as normal in age groups above eighteen years old.

The decision was therefore taken to use participants from a group with normal knee inclusion characteristics that were over eighteen years of age, as it was believed that this would reflect a better examination of the device's abilities and provide a more extensive database from which to construct the training group.

Further data required by the questionnaire asked about various biometric data of the participant. This data is currently locked by the software and thus is not used in the

production of output charts, it is still extremely valuable however as it can be related to the interpretation of the output charts and statistical results:

- The participants' age was required. The main determining factor for the cartilage degeneration seen in osteoarthritis is being 55 years or over. (Arden, Arden and Hunter, 2008)
- The participant's sex was required. The previous development of the phonoarthrometer was skewed towards females and a full evaluation needed a more equal distribution of data from both sexes. Adult males and females have differing skeletal structures that affect the way that they move, most importantly with regards to the motion of the knee is the differences in hip anatomy. Adult males have less wide hips than females this leads to a difference seen in the angulation and therefore gait observed between the sexes. (Dutton, 2008)
- Height in meters was recorded. Differences in height also lead to differences in the angulation and kinetic dynamic of the bones and hence the action of the knee joint
- Weight in kilograms was recorded. Increased weight puts a greater strain on the knee joint and the structures found within it
- From these previous two pieces of information body mass index can then be calculated using the standard formula:

$$\text{BMI} = \text{Weight (kg)} / \text{Height (m)}^2$$

BMI is useful as a recognized standard indicator of being under or overweight.

It does have its limitations however, as its assumptions about the distribution between lean mass (muscle) and adipose tissue (fat) are not always exact. As an example, since muscle weighs 30 percent more than fat, this can lead to individuals with a higher level of muscle (e.g.: athletes) being classified with a BMI that indicates being overweight or obese.

- Whether the right or left knee was tested was recorded; this was noted at the time of testing.

- The participants' level of activity is assessed on a scale of 1 to 5 in order to give an indication of how physically active the participant is with regards to the knee joint. A score of:
    - 1 indicates no or little physical activity, for example a participant with advanced osteoarthritis may give this where they are effectively chair bound
    - 2 indicates a level of day to day activity but no participation in sporting activities
    - 3 indicates a level of day to day activity and participation in some form of sporting activity involving the lower body at least once a week.
    - 4 indicates a heavier participation in sporting activities involving the lower body three or more times a week
    - 5 indicates an extreme schedule with participation in some form of sporting activity involving the lower body at least every day, for instance a morning and evening run. This score would be only given to someone training to dedicated athlete status.

These are the biometric variables as recorded during the development of the phonoarthrometer and it was assumed at that time that they were sufficiently important for the operation of the processing software and thus were intended to be incorporated at a later stage. In considering this assumption a number of further variables spring to mind both at the individual level and at the population level. Bone density, hydration levels and postural type are but a few examples of such variables. If all such variability could be accounted for by the system, it should give a perfect prediction of vibration output represented not as a corridor but as a line. If these multiple variables could all be measured sufficiently, a task that would be nigh on impossible and involve a number of invasive procedures, they could be included in the software. This would require extensive rewriting of the phonoarthrometer software; this is not the intention of this research. The intention is to test the limits of the system as supplied in its prototype form. It is therefore assumed that the 13 variable attributes (for full list see: appendix 2) derived from the angular velocity data alone supply enough information to give a prediction of the normal distribution of vibration response. It is however accepted that an abnormal response produced by the device could be due to these previously unidentified variables, the test

was whether the device gives a consistent response for healthy ‘normal’ knees as opposed to damaged ‘abnormal’ ones and how these compare.

3.31: Protocol.

For the purpose of this study the protocol was as follows:

Participants were asked to wear shorts for the investigation both so that clothing impacts on the sensors could be avoided and so that the knee joint could be easily accessed for the sensors to be attached to it. The participant was initially seated. They were then connected to the three non-invasive sensors namely the electro goniometer and 2 accelerometers by double-sided hypoallergenic adhesive tape as was specified for use with this equipment. See figure 9.

Once the sensors were securely connected, the device was then zeroed. Zeroing is achieved by asking the participant to stand, and to gently move their knee backwards so that it locks into a fully vertical position via the screw home mechanism of the knee joint. Participants were asked to remain in this position for a brief period whilst the sensors were set to zero, and then informed that they could relax.

This process sets the beginning of the angular trace to zero degrees that should in theory provide an indication of a fully extended leg and give a standardised point from which angular measurements can be taken. This can be identified as an assumption of the previous work. This starting point of full extension is achievable for participants with healthy knees, but whilst collecting data from osteoarthritic knees it was noted that a number of participants had decreased range of movement in their knee joint and could not extend the knee below 20 degrees, as the knee was zeroed whilst the knee was not in full extension the start point for this data will not be the same as for fully extended knees. In general this is documented by the clinician in charge of the participants and was carefully considered during the analysis stage as participants starting from 20 degrees rather than 0 degrees may obviously give a differing response to those that can fully extend the knee. This point will be discussed more fully in chapter 4.

The participants were then asked to perform a series of voluntary movements. All movements were quite natural for the joints concerned and should not have caused

excessive discomfort to the participant. However, if the participant experienced excessive discomfort at any point in the procedure and wished to discontinue then the procedure was stopped immediately. In the event of this happening any data collected up to this point would be stored and used only with the participant's agreement.

Participants requiring the use of walking aids, e.g. walking sticks or frames were allowed to use them throughout the session, without their use some of the osteoarthritic affected group could not have performed the walking part or sitting rising part of the protocol. The use of such aids, type and side used on, was recorded alongside the data for comparative purposes.

The motion activities that each participant were asked to perform are as follows:

Unloaded data:

1: Participants were asked to seat themselves with feet clear of the floor, and gently swing their leg back and forth ten times at a speed and angular range that was comfortable for them. This process represents one trace/file of raw data. This was repeated five times to produce five files of data. This is referred to as the swing (unloaded) protocol.

Loaded data:

2: Participants were asked to walk for five paces at a speed that was comfortable for them, then turn on the spot (or as near to on the spot as their range of movement allowed), and then to walk back to their starting position. This part of the protocol has been allowed for due to the device now using wireless technology this has a range of around 10 meters it was decided that 10 paces would be adequate to provide enough data whilst remaining within in the range of the device and not over taxing the participant. The turn on the spot would also provide new interesting data as at this point the knee joint is subjected to differing rotational forces as the knee joint is used to turn. This process represents one trace/file of raw data. This was repeated three times to produce three files of data. This is referred to as the walking (loaded) protocol.

3: Participants were asked to sit in a chair and then rise and re-seat themselves. Rising and reseating was collected as part of the protocol in the previous developmental work to give a example of how the phonoarthrometer would perform under loaded conditions (Abbott,

2008) however this was only conducted on a number of normal knees but did show that the phonoarthrometer could be applied to this data and give results. This was repeated three times with the participant ending in a seated position in the chair. This process represents one trace/file of raw data. This was repeated three times to produce three files of data. This is referred to as the sitting/rising (loaded) protocol.

The sensors were then removed from the participant, sterilized with antiseptic wipes and made ready for the next participant or packed away as necessary.

This concluded the protocol, the protocol took on average 15-20 minutes to complete from the point at which the sensors were applied to when they were removed, with allowances for talking to the participants and note taking with regards to specific information, the data collection generally fitted agreeably within the half hour slots allocated.

All data was collected to a laptop computer using the Biometrics Ltd. datalog software as supplied for use with the Biometrics Ltd. Equipment.

Initially data was collected at a 100 Hz-sampling rate as this was used in the previous development of the phonoarthrometer (Abbott 2008). This sampling rate was chosen in the developmental work as it allowed comparison with an optical motion tracking system that had a maximum sensible sampling rate of 100Hz, as faster rates risked burn out to the sensors. However, this optical motion tracking system was not used with the final prototype phonoarthrometer. Early on in the data collection phase of the current study it was identified that there was a problem with this sampling rate as gaps were appearing in the angular range of the data collected greater than three degrees.

The implications of this will be discussed in greater detail in the following chapter (4) however it should be noted at this point that the sampling rate was changed from 100Hz to 200Hz. This increase was possible as the accelerometers could operate at rates higher than 100Hz; several higher sampling rates were tested, however at higher rates the data processing time taken by the phonoarthrometer software increased. 200Hz was selected as the best compromise to solve the sampling rate issue, whilst not increasing the data processing time too severely. In effect the size of the gaps halved as the sampling rate was doubled.

The final sample size for the study was 67 individual healthy knee joints and 30 individual osteoarthritic affected knee joints.

Each participant generates multiple readings of data with typically five recordings from the swing (unloaded), three from walking (loaded) and three from sitting/rising (loaded) parts of the protocol within these recordings the data is then further subdivided into each flexion/extension sequences as determined by the phonoarthrometer's analysis software which recognizes sequences of flexion and extension within the data by changes in the angular motion. As an example this typically resulted in ten flexions and extensions for the swing (unloaded) sequence as the leg is swung backwards and forwards ten times.

The device is diagnostic in nature and as such not a treatment. So determination of how many participants were required to form an appropriate sample size was dependant upon the validity of the final results produced and whether the collected data is sufficient evidence to support the eventual use of this device as a mainstream tool for detection of osteoarthritis. Satisfaction that the results from this study are directly comparable with other research in this field is of key importance to proving the validity of this study rather than the testing of a population.

Previous published papers (Krishnan et al, 1997) have shown data sets of up to ninety individuals, including data taken from both healthy and diseased/damaged knee joints as their sample size; this therefore seems an appropriate minimum level for the sample size to give comparable validity to this study and the study exceeded this level.

3.32: Ethical considerations.

As this study required the participation of human respondents, and a large part of the work was conducted upon NHS site at Basildon hospital it required ethical approval. The ethical application for the research was carried out using the NHS Integrated Research Application System (IRAS). The consideration of these ethical issues was necessary for the purpose of ensuring the privacy as well as the safety of the participants. Among the significant ethical issues that were considered in the research process include consent and confidentiality. In order to secure the consent of the selected participants, the researcher relayed all important details of the study, including its aim and purpose. By explaining these important details, the participants were able to understand the importance of their

role within the research. The participants were also advised that they could withdraw from the study at any time.

To maintain the confidentiality of the participants, each consent form was assigned a unique number, which was used to identify individuals on all other materials. The only place where this number and the name of the participant were available is on the consent form itself. These were stored in a locked cabinet within the Principal Investigators office, which was also locked. Data stored within the neural database of the phonoarthrometer is not even attributable to this ID number and is therefore even further anonymised. It is possible to locate the ID number of the current participant whose data is being processed, but only with extensive knowledge of the system source code and manually monitoring data flow whilst the system is operating. The anonymity of all participants was therefore assured.

Ethical approval was gained from the Norfolk Research Ethics Committee on October 20th 2010 REC reference number: 10/H0310/41

3.4: Analysis.

Analysis of the collected data involves the processing of the raw data using the phonoarthrometer software. This software allows the construction of prediction output charts showing the predicted response of a normal knee joint as a series of points corresponding to maximum and minimum values for degrees of arc during flexion/extension sequence of the knee. The actual data recorded is then plotted in comparison and deviations outside these values should indicate an abnormal knee joint response.

3.41: Use of the phonoarthrometer software to process raw data.

The software used in the processing of the raw data can be described as a hybrid machine learning architecture, essentially an expert system that merges aspects of a neural net and a database search system.

The use of the software that is vital to the operation of the phonoarthrometer required an in depth training period for the researcher. The order in which the raw data is inputted is of vital importance as any mistake at this stage could result in the system being unable to recognise an abnormal response at a later stage. Firstly the collected data trace was imported in ASCII format from the stored datalog software file. In order to use the software the raw data collected using the datalog program must first be exported and converted n ASCII format to a txt.file. This file is then used by the main code of the phonoarthrometer software, as accessed through the visual basic program, to produce the prediction output charts and from these a final statistical output. These are then used for visual inspection (output charts) and then statistical testing (final statistical output file) to assess conformity to the generated prediction corridor.

Alongside this file changes must be made to the participant variables recorded within the main code. These are:

- Flexion type and file number (e.g. Right knee flexion extension 1:rkfe1, Left knee flexion extension 5: lkfe 5)
- The previously recorded biometric data from the questionnaire is then inputted this is locked and not therefore directly used in the production of output charts but it is added with the aim of including these population level variables at a future time as the database of normal recorded data grows:
    - Age (yrs)
    - Sex (male/female)
    - Weight (kilograms)
    - Height (meters)
    - BMI (weight/ height squared)
    - State of joint (normal/abnormal, as defined from the inclusion exclusion criteria)
    - And participants' level of activity (scale 1-5)

Once these details are entered the txt. file is ready and the software can be run. The file is imported and divided up into flexion/ extension sequences based on changes in the angular motion. The software does this by scanning along the angular trace using a windowed system that detects the direction of motion and the point of change, it then crops the data at these points.

Once individual flexion and extension sequences have been isolated the system then takes each angular degree point and extracts a number of informational characteristics from it. These are explained in more detail in the following three subsections:

1) Firstly it determines attribute one; this is the prime attribute as identified in the developmental work for the phonoarthrometer (Abbott, 2008). This attribute is termed the microstructure motion type and is derived from small scale fluctuations in the angular velocity of the motion. Each microstructure motion type is classified in the following format: Type/Class/Position.

Type**:** refers to the acceleration/constant/deceleration characteristics of the motion and conforms to 1 of 13 combinations as identified by Abbott (2008). A full list of all 13 types are provided in appendix 2.

Class: refers to the classification of each variable of Type. Figure 13 illustrates this point.

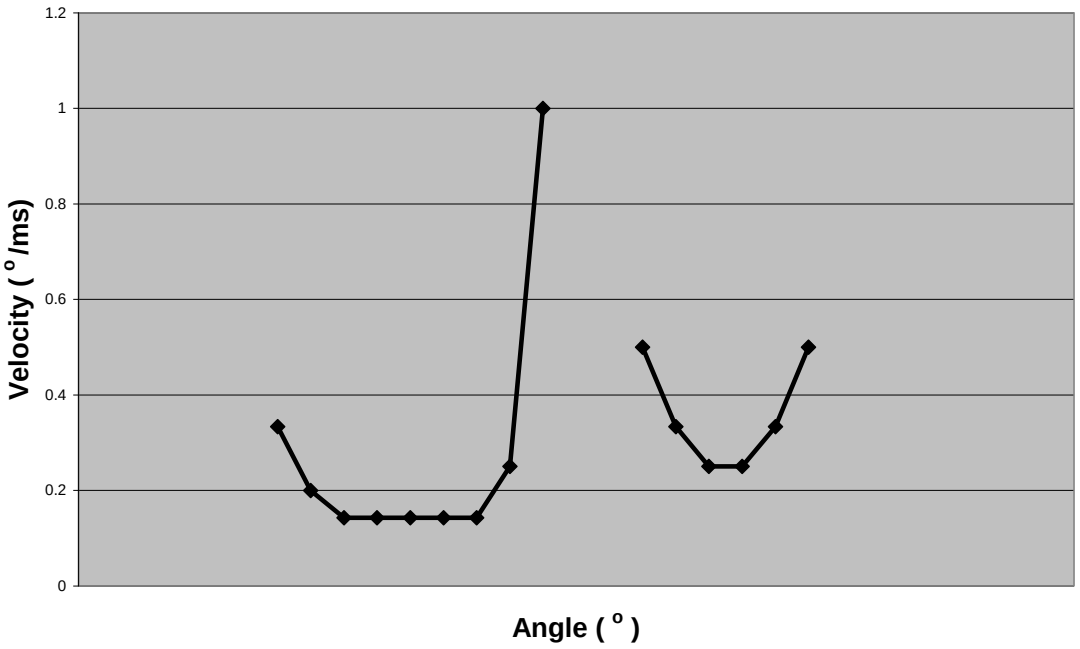


Figure 13. An example of two type 1 microstructure motion types with differing Class structure (from Abbott, 2008)

In this example it is clear that both angular motions are type 1, a period of deceleration followed by a period of constant velocity followed by a period of acceleration. However, the structure of each deceleration, constant velocity and acceleration phase is variable between the two and requires a method of differentiating them thus they would be classified as Type1/Class1 and Type1/Class2 microstructure motions.

Position (Pos): refers to the position of the degree of arc within the microstructure motion type. For example if a microstructure motion Type1/Class1 has an angular range from 20° to 26° then the microstructure motion type at 20° would be assigned the sub-format of Pos1, 21° would be assigned Pos2 and so on with finally 26° being Pos7. Figure 14 gives an illustrative example of how each angular point is classified by microstructure motion

type over an angular range.

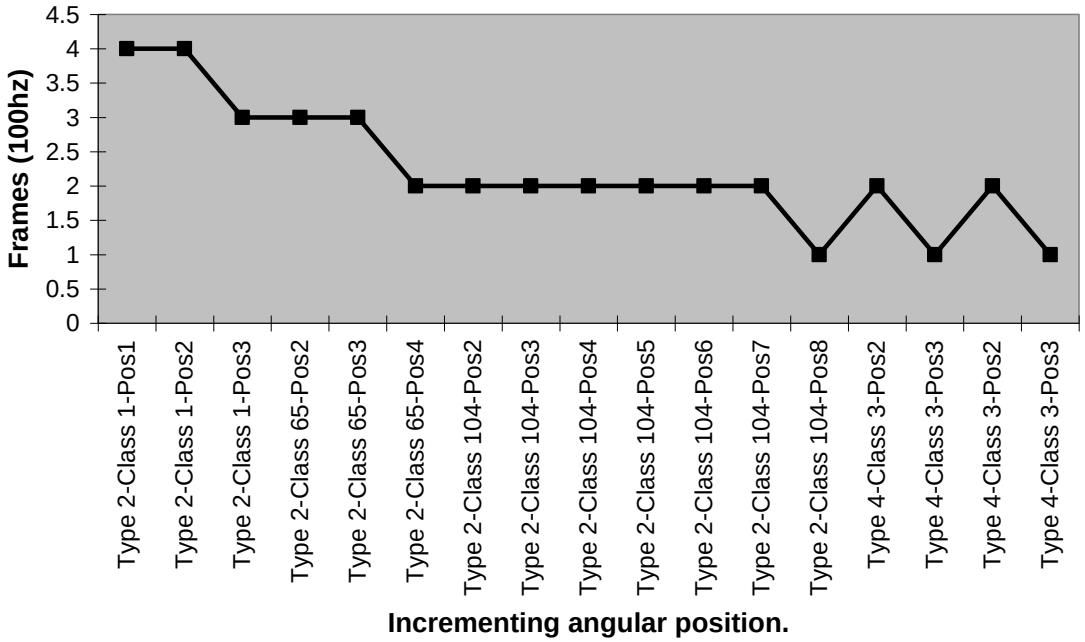


Figure 14. Example of the classification structure of microstructure motion types for each point in an angular range. (From Abbott, 2008).

One further point of note must be made with regards to the assignment of the Position characteristic. The only position 1 (Pos1) denoted in the above figure (14) is at the first angular point, subsequent microstructure motion types start with the Pos2 classifier in place, what is actually occurring here is that the completion point of each microscale motion type is also the first point of the next motion. This point is discussed more fully by Abbott (2008) and rather than repeat it here it is sufficient to point out that only the first angular point in a microstructure motion type will be classified as Pos1.

2) Next a further 12 attributes are derived from the angular velocity of the flexion/extension sequence for each angular degree point. These form a subset of values linked to the microstructure motion type and are hierarchical in sequence running down the list from attribute 2 through to attribute 13. This is important as the hierarchy determines the sequence that these attributes are used as search terms in the final database. These 12 attributes together with the microstructure motion type already explained can be thought of as weighting variables as used in a standard neural net architecture.

3) Finally a further three values are extracted for each angular degree point. These correspond to each of the X, Y and Z axes of the accelerometer and are derived from the recorded vibration response of the flexion/extension sequence. At each angular point a value for the vibration response is calculated, this value is termed Total Absolute Amplitude (TAA).

Total absolute amplitude is the method employed for normalisation of the vibration response to each degree of angular arc; all values of joint vibration are de-signed to positive value and simply totalled for each degree. If, for example, there are five frames of data for 20° and three frames for 21° then the values in the five frames are summed to give a single value for 20° and 5 is recorded separately. The three values for 21° are summed to provide a single value for 21° with 3 recorded separately, and so on. The values are de-signed the reason for this being that the raw data from joint vibration recordings are produced as waveform data, they can obviously therefore have negative values. If all such values were simply totalled, the negative would cancel out the positive; therefore all negative values are de-signed and treated as positive. The resulting value from this procedure may effectively be considered the area under the waveform graph per degree of arc (Abbott, 2008). Figure 15 below gives a simplified view of this process.

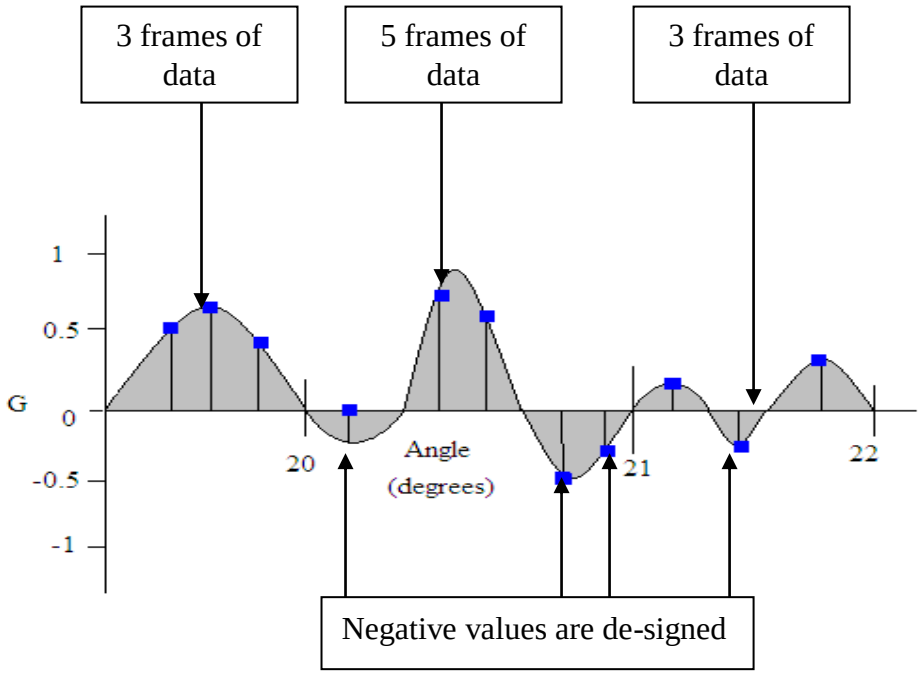


Figure 15. Calculation of Total absolute amplitude (TAA) from accelerometer waveform data.

Once calculated the three values are linked to the 13 attributes already described.

So in summation, for each angular degree of arc in a flexion/extension sequence a number of classifier values are derived. These are the microstructure motion type, 12 attributes from the angular velocity of the motion and three linked total absolute amplitude values from the vibration response corresponding to each of the X, Y, and Z axes of the accelerometer. This may be viewed at its most simple as a means of linking any given vibration response to the precise set of circumstances that produced it. This statement represents the core algorithm behind how the system functions

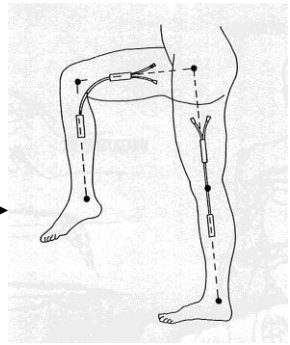
The next step in the operation of the phonoarthrometer software requires the construction of a database, termed the microstructure library; this phase is analogous to the training phase that would be employed in the operation of a standard neural net. The microstructure library is comprised of stored microstructure motion types (prime attribute) each correlated to a subset array of the further 12 attribute values and the linked vibration response values (total absolute amplitude) for each of the accelerometer axes. In order to construct the microstructure library a subset of normal, healthy knee recordings are inputted into the system. Values derived from these are then stored and collated to be used as a database of searchable terms for the construction of a prediction of a normal knee response. The building of the microstructure library is explained further in the following chapter (4).

3.42: Operation of the phonoarthrometer software to run a scan.

Once the microstructure library has been constructed the phonoarthrometer system can be operated to perform a scan of the data.
Figure 16 gives a diagrammatic view of how the core algorithm operates.

Tested knee joint

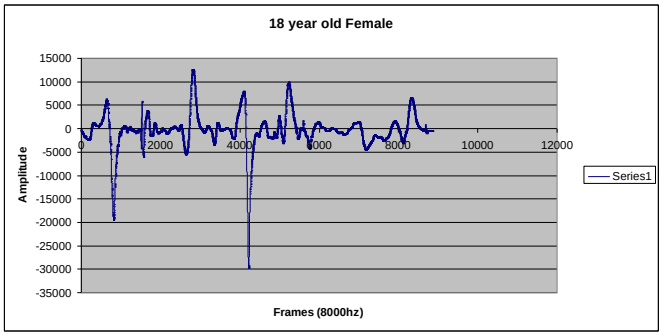
Motion recording (from tested knee)

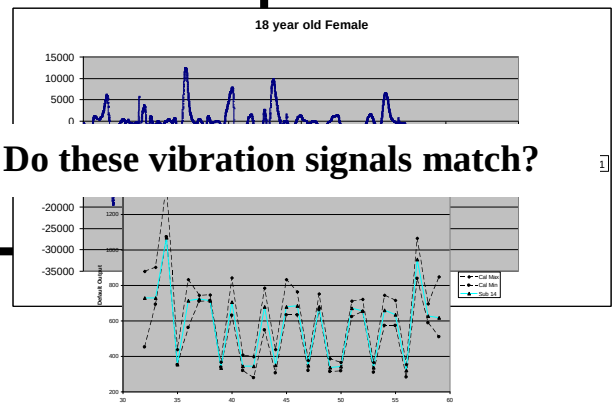


Prediction of vibration signal constructed from stored database of normal knee recordings

Parameter 1	Parameter 2	Parameter 3	Vibration signal

Vibration signal recording (from tested knee)





Output chart

Figure 16. Diagrammatic representation of the operation of the phonoarthrometer core algorithm

In order to do this the vibration response and angular trace of a given recording is inputted into the system, it is then segmented into flexion/extension sequences and microstructure types and angular velocity attributes are determined from it. Critically however, these are not stored in the microstructure library database but run through it using each of the 13 attribute values (microstructure type plus the 12 further attributes) as searchable terms, these can be thought of in a similar way to 'key word' in a standard database system. It does this in an (artificially) intelligent way attempting to find best matches if exact matches are not possible.

As noted previously it is the microstructure motion type, as the prime attribute, that is first searched for, the best match for this is then isolated and leads to a subset array containing the further 12 angular velocity attributes linked to TAA vibration response values for each of the X, Y and Z axes of the accelerometer. The software then extracts the TAA values of the best matches from each array, a minimum of 2 'matches' are selected.. Figure 16 gives a diagrammatic representation of this process.

The TAA values are then numerically ordered and the maximum and minimum values extracted and plotted for the corresponding degree of arc. It does this for each angular degree point in the flexion/extension sequence providing a corridor of prediction for what a normal knee response should produce, the lowest value of TAA being the lower prediction limit the highest TAA value being the upper prediction limit. In effect these two values can be considered the limits of a normal distribution that sits across the prediction.

Once the prediction corridor has been plotted the actual vibration response TAA values are plotted for each degree of arc in the flexion/extension sequence. The resultant plot of prediction with the actual response values superimposed is termed the output chart for the flexion/extension.

.

3.43: Output charts.

These show the corridor of prediction points as generated by the phonoarthrometer software with the actual vibration response total absolute amplitude values being overlaid, an example is given in figure 17.

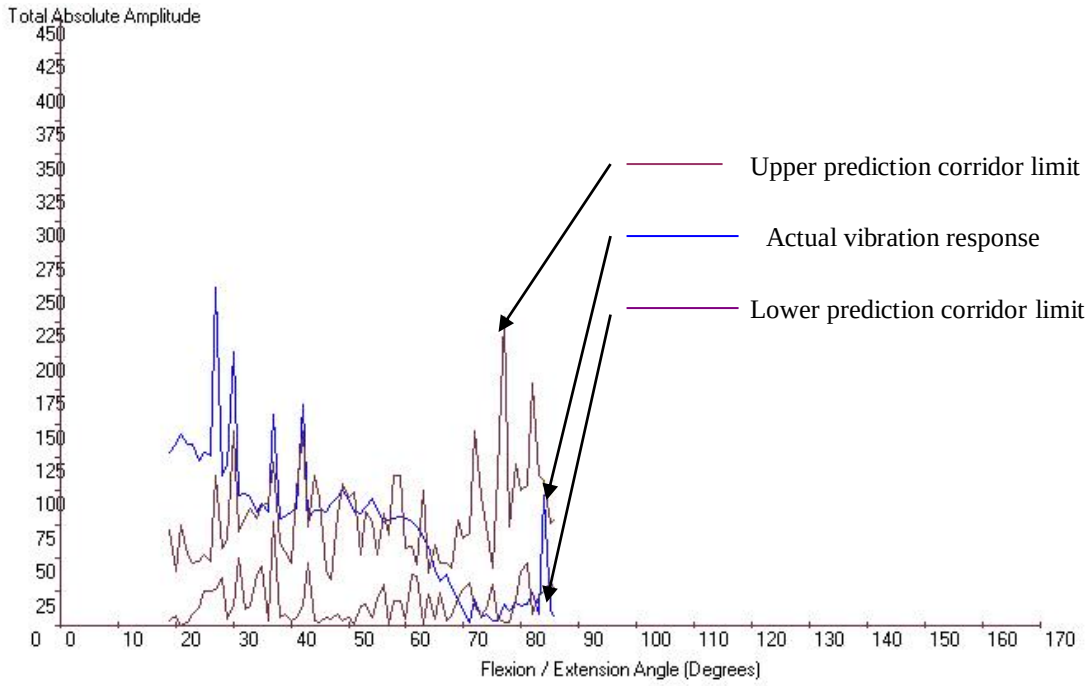


Figure 17. Example output chart.

If the phonoarthrometer is operating as expected then a normal healthy knee joint should lie within these boundaries whereas an abnormal response will deviate from this prediction corridor.

At this point it is worth considering what a response outside the prediction corridor actually means. The prediction corridor represents how the joint should respond in terms of vibration, based upon the stored and learnt information within the database. As all the stored data in the system is from individuals with knees uninjured and free of pain, it may be inferred that this is a prediction of the response for a normal knee. However, this definition of normality is equally bounded by the population characteristics of the training group individuals recorded. A response deviating from the corridor, suggestive of abnormality, could therefore simply be a population related difference, for instance, a higher recording for a 60 year old may not be abnormal for that age, just different to the response of a 20 year old, and so on.

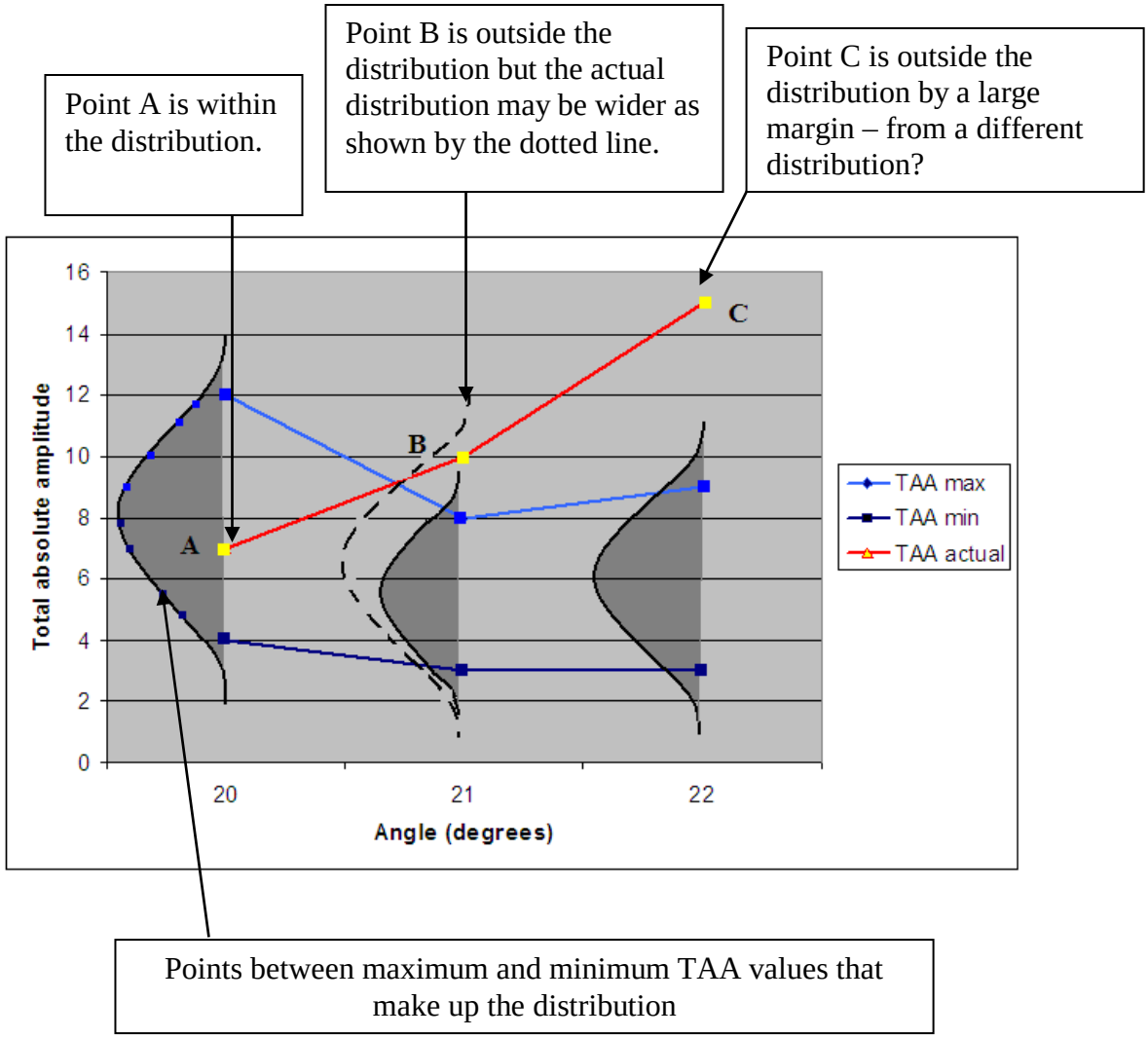


Figure 18. The relationship between the maximum and minimum prediction values and outlying points.

The above diagram (figure18) shows the relationship between outlying points that do not fall within the maximum and minimum prediction lines (the prediction corridor). As can be seen point 'A' is within the prediction corridor, it can be considered therefore to be part of the normal distribution of total absolute amplitude values that make up the prediction, it would therefore be considered a normal response. A number of further points are shown on the distribution curve; these represent the TAA values for points falling between the minimum and maximum TAA values that are plotted on the actual output chart. For each individual angular point the number of points will vary depending on how many matches the software finds within the database. As a generalised figure typically around 20-30 points are selected by the software to plot this distribution but without delving deep within the core system for each individual point the exactitude of this figure cannot be known.

However, it can be inferred that the greater the number of points that make up this distribution the closer the distribution is to its complete form.

Point ‘B’ is an outlier to the prediction; however, caution must be exercised when classifying it as an abnormal response, this is due to it falling by only a small margin from the upper prediction line. In this case point ‘B’ may simply represent one of the responses not yet seen by the system, it in effect represents a point found within the tails of the distribution, and indeed may represent that the distribution curve is incomplete and therefore should be shifted to a new curve (as represented by the dotted curve).

Finally, point ‘C’ is also an outlier to the prediction; it is likely in this case that it is an abnormal response as it falls by a large margin from the upper prediction line it is therefore unlikely to be from the distribution of normal knee responses.
However, once again caution must be exercised with this conclusion, as if the number of TAA value points extracted by the system is low then the prediction corridor may represent a largely incomplete distribution of normal knee responses and once again point ‘C’ may be representative of an extreme outlier

This in effect means that individual output charts and individual angular points from them can only be used as a guide to differentiate a normal knee response from an abnormal one. In order to provide a more conclusive differentiation a consistent response must be observed across many individual angular points and output charts, to do this a number of statistical parameters must be shown regarding both the number of points that fall as outliers and by how far they fall from the prediction corridor, these are more fully explained in the following section 3.44.

The next point requiring discussion is to elaborate on the relative upward and downward shifts of the values. Firstly it must be recalled that the values have been normalised by totalling values for each degree of arc. With this in mind, the relative shifts up and down from one degree to another are being skewed to some extent by the shift in angular velocity. The developmental study by Abbott (2008) considered that this could be normalised out by averaging for angular velocity, however, this was not done. This is due to the averaging process turning what is an actual data value into an estimated value. This transition from real to estimate was not deemed appropriate and the values were left as

real data values. The prediction lines shift relative to this artefact, as the number of frames used to cover each degree of arc makes up one of the attributes being taken into account, thus each point may still be easily identified as normal or abnormal. One must however be careful not to try to draw conclusions from relative vibration values for each degree of arc at this time.

This being said, there may be an observed correlation between certain angular ranges in individual output charts, for instance where the plotted lines start at a generally high value and then decrease to a steady range of values, this may represent a general sequence of mechanical action within the knee. To give an example, higher values may be found in the angular range of 0° to 30°; this represents the angular range covered in the screw home mechanism of the knee joint, by which it locks into a fully extended position. Consistently high values found in this region would indicate that this part of the angular range produces a greater vibration signal than subsequent motion; this would only be comparable in terms of the overall pattern being consistent between individuals as the actual TAA values plotted would not be comparable.

This also in part explains one further observation, that an a plotted actual vibration signal from an abnormal (osteoarthritic) knee can start outside the prediction corridor at a higher value than the maximum prediction line and then through the course of the flexion/extension angular range pass through the prediction to end up below the lower prediction line. In this case this represent a change in the vibration output of the signal as it travels through the flexion/extension angular range and suggests evidence of differing vibration responses being produced as differing areas of the knee joint surfaces come into contact, for instance an abnormal response in the first 30° of angular range but not in the subsequent angular range could indicate that the osteoarthritic changes are only seen in the articular surfaces involved in the screw home mechanism.

The output charts can be considered a useful visual guide to what is occurring within the joint however, they are only really interpretable at an individual level. In order to provide the objective testing of the phonoarthrometer's ability that is required in this study they must be further analysed via statistical means.

The ability to carry out such a statistical analysis the phonoarthrometer produces alongside the output charts a file of final statistical output. This allows the collation of data regarding how many of the points fall as outliers to the prediction and by how far they deviate from the prediction. This file can be imported into a normal excel spreadsheet for further analysis. An overview of this process is given in the following section

3.44: Statistical analysis.

As previously described the phonoarthrometer produced output charts showing the predicted response of a normal knee joint as a series of points corresponding to maximum and minimum values for degrees of arc during flexion/extension of the knee. The actual data recorded is then plotted in comparison and deviations outside of these values should indicate an abnormal knee joint response.

The number of points outside and distance of these deviations from the prediction corridor was then treated statistically to establish their degree of significance. From each output chart (produced from each flexion/extension sequence) a number of values can be calculated.

Before this process is explained some consideration must be given to the terminology of 'error' that is used in this study. It could be considered that error is the wrong term for deviations from the prediction corridor as this can be seen even in both examples of normal knees and abnormal ones. These could simply be described as points that fall into the tails of the plotted distribution for the normal knee or from a different distribution in the case of the osteoarthritic ones; however, this differentiation of points into categories before analysis suggests that a normal response can already be determined from an abnormal one. Therefore the term 'error' was applied as a generic term to describe deviation from the prediction corridor, further as this is how the categories are labelled in the final statistic output file it was decided that for the sake of congruency the term would be retained.

Firstly for each chart the percentage error is determined. This is simply the number of points falling outside prediction line expressed as a percentage of the total number of points (corresponding to the range of degrees in the Arc):

- Percentage error minimum is calculated for points falling below the prediction range. For example: given an 80degree arc of flexion/extension where 20 points are below the predicted line will give a % error min. of 25%
- Percentage error maximum is calculated for points falling above the prediction range. For example: if a further 20 points are above the predicted line this will give us a % error max. of 25%.

Figure 19. Shows a simplified example of the calculation of % error maximum and minimum.

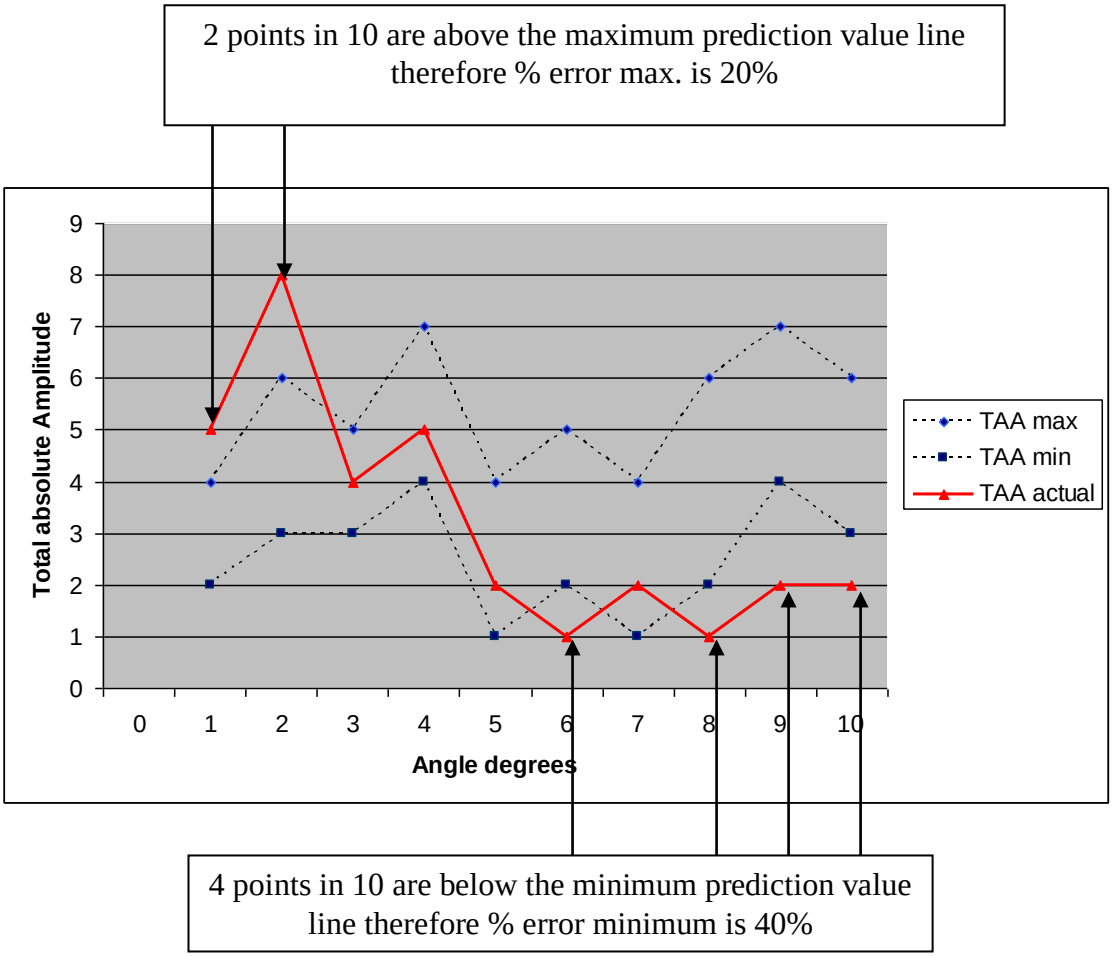


Figure 19. Calculation of % error maximum and minimum from the output charts.

Percentage total error can also be given by the summing of these two numbers. Using the above examples: % error min. of 25% + % error max. of 25% produces a % total error of 50%.

The percentage error gives an indication of how well the actual data fits to the prediction corridor, a high value for either % error min. or %error max. Indicates that very few of the overlain data points fall within the prediction corridor conversely a low % error min or %error max indicates a good fit of the actual joint vibration to the prediction. Hence low % errors would be expected for normal/healthy joint signals and higher % error would be expected for abnormal/osteoarthritic joint signals.

Any new data shown to the system has potential for it to include previously unseen responses. This can be attributed to the inherent variability found within the knee joint signal, the system does not seek to account for all of this variability, if it could do so then a perfect fit to the prediction could be found and no points would deviate from it. This result of this is that some degree of error (points outside the prediction corridor) is observed even in the control group of normal knee responses. The important point is that for the system to work the degree of error seen in the control (normal) group should be less than the degree of error seen in the osteoarthritic (abnormal) group.

These values given by % error are however not sufficient to describe whether a response can be classified as normal or abnormal, consideration must be given to how much of a deviation from the prediction these points show.

The upper and lower points of the prediction corridor can be thought of as representing the extreme tails of a normal distribution for a normal knee response. Points that do not fall within these boundaries are outside this distribution; if this distribution was complete and fully reflected the potential distribution of the population then points outside could be classified as abnormal. However the distribution is not complete it is generated from the 13 variables calculated from the angular velocity data, these are considered to be sufficient to describe the biomechanical nature of the joints motion but by no means account for all factors influencing the variability of the joint signal. Thus for each angular point the degree of deviation for each point above or below the prediction gives an indication of whether the point belongs to the predicted normal distribution or whether it comes from an entirely separate distribution for abnormal responses.

In order to quantify how far points fall from the predicted range the following was calculated:

- Average error min. is the difference between the value* of a point below the prediction range minus value* of the lower prediction line for that point. The values of all points below are then summed and divided by the number of points, giving the average departure of all points below the minimum prediction for each motion as measured against the y axis
- Average error max. is the same as for the Av. error min. but uses points above the prediction range and the upper prediction value*, giving the average departure of all points above the maximum prediction for each motion as measured against the y axis

Figure 20 gives a simplified example of the calculation of average error maximum and minimum.

* It is important to note here that the scale used for each point is applicable to each individual point and the distance from the prediction line measured to that scale, the scale is not congruent between points falling at differing degrees of arc within the flexion/extension.

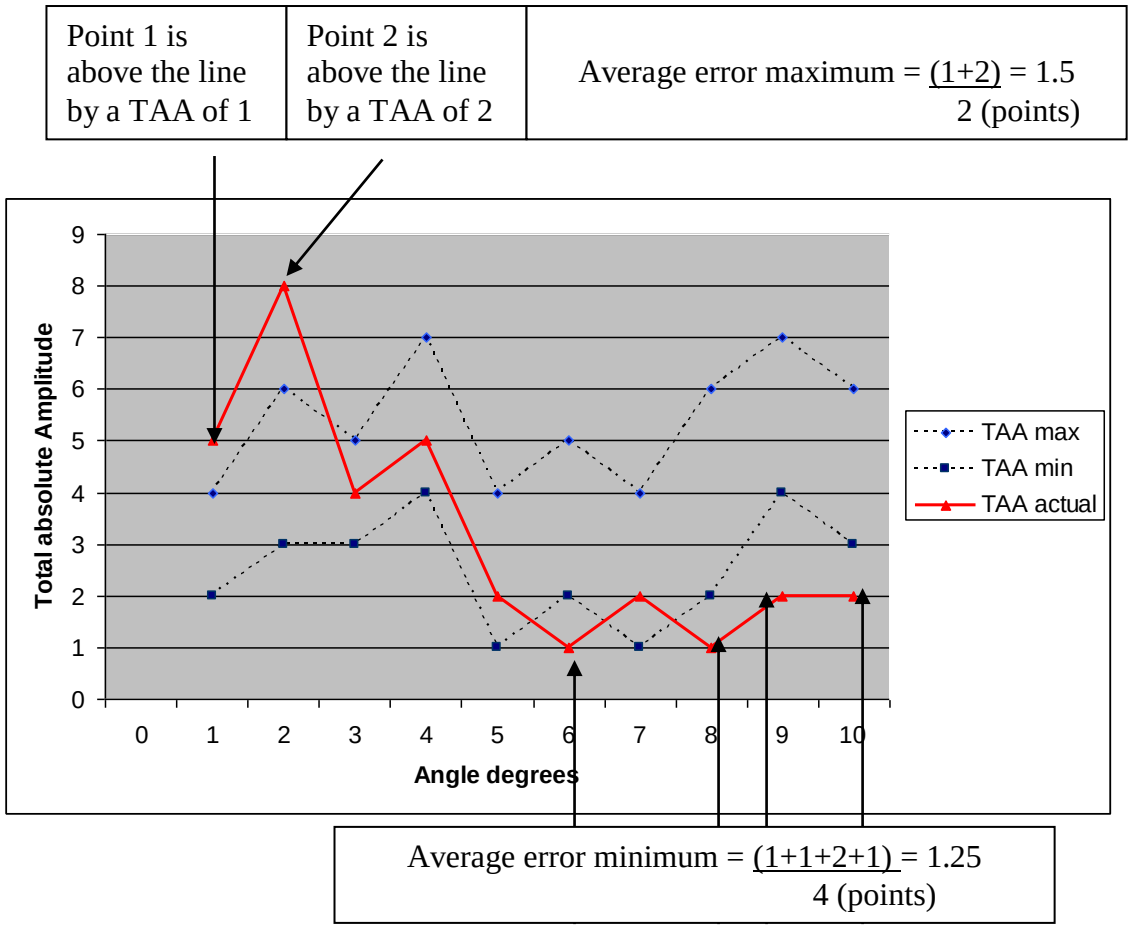


Figure 20. Calculation of Average error maximum and minimum from the output charts.

A high value for average error maximum or minimum indicates that the points that fall outside the prediction corridor are a large distance away from the upper or lower predicted values, if after statistical testing this is shown to be a significant departure when compared to the control group of normal responses, it would indicate that these values are not from the same distribution as the normal response and would indicate an abnormal response.

In contrast low average error maximum or minimum would be seen in a joint response that comes from the predicted distribution for normal joint responses, the points falling above or below showing no significant deviation from the prediction.

Average spread can also be calculated this being the difference between the upper and lower prediction range (the spread) for each point, summed and divided by the number of points.

This value was an important indicator of how well the system is stabilised in terms of data starvation, as a more stabilized system should have a lower value when compared to a less stabilised one. Average spread will also be an important checkpoint when comparing data from two different output charts, as if the system is stabilised, there should be no significant difference between the values produced from differing charts.

As stand alone values average error min., average error max. and average spread are useful indicators of how far the observed data deviated from the predicted range and how precise the predicted data is. More importantly however, these 4 values (% error min, %error max, Average error min and Average error Max) will be used to allow the comparison of different output charts, via the performance of a t-test, allowing it to be shown whether the results are statistically significant between differing charts and thus allow us to see whether anything important is occurring or not.

These 4 values are calculated automatically for all output charts available in each of the files of data, and then outputted as a .txt file. Means and standard deviations can then be calculated for both the osteoarthritic and control data.

As it was decided most sensible to simply compare means and standard deviations from the control group with the osteoarthritic group, a t-test was used. This simple test provides transparent and easily interpretable results for the large amount of data that was analysed, providing succinct demonstration of the phonoarthrometer's ability to detect joint abnormality.

The t-test could be either one or two tailed but after consideration a two tailed test was decided upon. At first appearance a one tailed test would appear to suffice as any values significantly lower than the prediction parameters would indicate a better fit to the prediction.

However looking at the output charts produced indicated that being able to detect better levels of fit to the prediction as well as poorer had value. Two tailed tests were therefore carried out and any negative values of significance recorded.

This ability to produce viable statistical results was important in particular when comparing output from the osteoarthritic knee group and the control group of normal knee

joint data. If statistically significant deviation from the prediction corridor was found for the osteoarthritic data and no statistical significance is shown for the normal control group, it will be strong evidence to support the detection ability of the phonoarthrometer.

3.5: Summary.

This chapter has presented the aims and objective of the study, as well as the overall methodology behind the research. It provides a detailed description of the operation of the core algorithm and an understanding of how the analysis of the vibration signal is used to produce output charts and from these the final statistical output.

The following chapter discusses some considerations encountered in the actual use of the phonoarthrometer and presents the results from the experiment involving the placement of the accelerometers at differing positions around the selected optimum anatomical positions.

Chapter 4

Critical evaluation of the phonoarthrometer system.

4.1: Introduction.

This chapter is concerned with the realities and practicalities of using the prototype phonoarthrometer and provides a critical evaluation of the phonoarthrometer system. It defines, identifies and explains the problems encountered in its use for data collection and the subsequent software processing of that collected raw data. This proved to be an important section of the research, as it was through the practical application of the phonoarthrometer that a number of limitations to its present, prototype design were identified.

Any difficulties in using the phonoarthrometer as a medical tool in its existing state will be discussed, including any incompatibilities with the protocols as described in the previous chapter

The use of the phonoarthrometer software and any potential problems identified and their context within the production of the final results will be considered. This encompasses any problems encountered in using the software to process the gathered raw data and any problems arising from the operation of the software.

An explanation of how the training group was selected and used to build the core microstructure library is given.

Finally a section will detail the preliminary experiment that was designed to test the limitations of the prototype phonoarthrometer's ability dependent on the accuracy of the placement of the two accelerometer sensors in the correct position on the patella and medial joint line.

4.2: Data collection.

4.21: Observed Physical differences in osteoarthritic knees and healthy knee joints.

It was observed during the course of the research that the osteoarthritic knee joint group differed in a number of obvious ways from the healthy/normal knee joint group.

Before any testing involving the use of the phonoarthrometer was carried out, it could be seen that the osteoarthritic knee joint group had generally a more antalgic gait (characterised as a limp adopted so as to avoid pain on weight-bearing structures), and moved slower and more carefully due to the pain in the joint. The osteoarthritic group also showed a marked decrease in the range of movement capable of the knee joint. These observations have been noted in other studies (Tanaka and Hoshiyama, 2012)

Due to these factors participants from the osteoarthritic group, particularly those at an advanced stage of osteoarthritic change in the knee joint, often experienced a greater level of difficulty completing the test protocol.

The osteoarthritic group also tended towards a greater proportion of participants with high BMI's meaning that often the knee joint itself was covered in a substantial layer of fatty tissue. This frequently made the knee joint larger and increased the difficulty with which the selected anatomical landmarks were located.

It should be noted that a number of participants from the group of normal/healthy knees with high BMIs also suffered from the same problem. However, the proportion of participants with high BMIs in this group was lower.

The osteoarthritic group also exhibited a number of co-morbidities associated with their osteoarthritic condition. It should be remembered that osteoarthritis is a complex condition embracing a spectrum of degenerative change. In many cases this meant that although the knee was diagnosed as osteoarthritic it was also accompanied by a diagnosis describing additional damage for instance a meniscal tear or a ruptured anterior cruciate ligament.

In summary, it was therefore often apparent before any testing that the osteoarthritic knees would behave in a manner different to that of a healthy knee joint from the normal subset.

The ability to account for any variability introduced by these factors is important in the evaluation of the system. This therefore poses the question - are any differences seen in the final results due to the differences in the way the knee joint behaves and not in the vibration response generated from it?

The answer in this case should be no. Why? Because all the final data output is constructed from basic set of microscale motion types linked to vibration responses stored in the microstructure library. If the osteoarthritic knee joint was using different microscale motion types to that of a normal healthy knee then this would be reflected as a whole new set of microscale motion types being uncovered each time an osteoarthritic knee was tested (for an explanation of the microstructure library and its function see later in this chapter). This was not found to be the case.

4.22: Speed of knee joint movement.

As part of the protocols it states that there is no constraint placed on the speed at which the knee joint was moved, merely that the joint should be moved at a speed that was comfortable to the participant.

It was noticeable that some participants moved their knee joint slowly and deliberately and others with speed and energy. This variability is vital to the successful testing of the phonoarthrometer as a prototype device. In order for the phonoarthrometer to be a potentially useful device it must be able to account for this inherent variability in its analysis.

It will be recalled that previous attempts to analyse knee joint vibration signals have attempted to remove this inherent variability through controlling the motion of the knee joint, often using expensive equipment such as the Biodex Isokinetic Dynamometer chair designed to move the knee at a constant rate independent of the participant being tested (Jiang et al., 1994). It was precisely in order to avoid the use of such constraining (and

expensive equipment) that the phonoarthrometer was developed and its ability to accommodate the joints natural variability in angular velocity.

In this case, how would this difference in the speed of movement of the knee joint affect the accuracy of the results from the gathered and processed data? In theory it should not as the final processed results are a constructed output that the phonoarthrometer produces from the microstructure motion library and therefore any output is constructed from already recorded differences in the angular velocity of normal/healthy knees.

Once again if the significantly slower moving joint were producing microscale motion types as previously un-encountered and unrecorded to that of motions of the normal/healthy knee of the group used to train the phonoarthrometer, it would be seen as a significant increase in registered microstructure files on every abnormal osteoarthritic affected knee joint tested.

For future reference it would therefore be an interesting experiment (but at time of this research considered too time consuming and diverting from the purpose of the study) to conduct a range of tests that recorded the length of time taken for the participant to complete the protocol. Variation in time taken could then be assessed as to whether it had any affect on the final data and whether extreme cases with regard to the time taken (both fast and slow) had any affect on the data gathered.

4.23: Differences in the appearance of the data for the different protocols.

Below are included a number of examples of the raw data as collected from the knee joints of participants using the datalog hardware.

In all cases the oscillating line (coloured pink) represents the angular trace of the electro-goniometer in the sagittal plane.

The other lines of variable wave motion at the centre of the graphs are the vibration responses as recorded by the patella and medial line accelerometers on channels of x y and z.

As can be seen in all cases these lines are variable over their duration and cannot at this stage be used to presume anything about the nature of the knee being tested, in deed they are inherently variable between each individual participant's motion and for each motion-type protocol.

The purpose of including these examples of raw data is to illustrate the difference in the associated angular traces of each protocol motion type. An understanding of this is necessary to understand how the subsequent software processing effectively isolates flexion and extension sequences in the data and why the phonoarthrometer software may have encountered more difficulty in processing some types of motion as opposed to others.

It should also be noted that in order to process this raw data it is first converted to a text file to allow the phonoarthrometer software to process it.

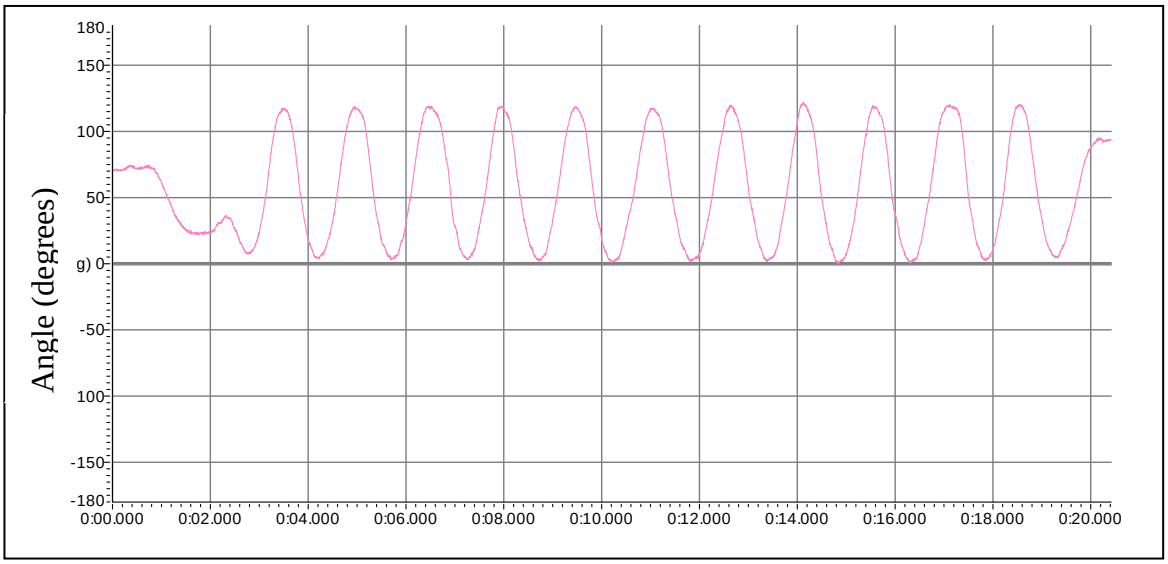


Figure 21. An example of an angular data trace as recorded by the electro-goniometer taken from the flexion/extension swing motion protocol of subject 02 right knee first trace.

The above graph (figure 21) shows the angular trace from the swing (unloaded) of subject 02 right knee, trace first recorded trace. The flexion extension sequences are clearly defined, ranging from near 0 degrees (fully extended leg) to approximately 120 degrees

(fully flexed leg). The above example shows only the electro-goniometer recording of the trace.

The raw data also records the vibration response an example of which is presented in figure 22.

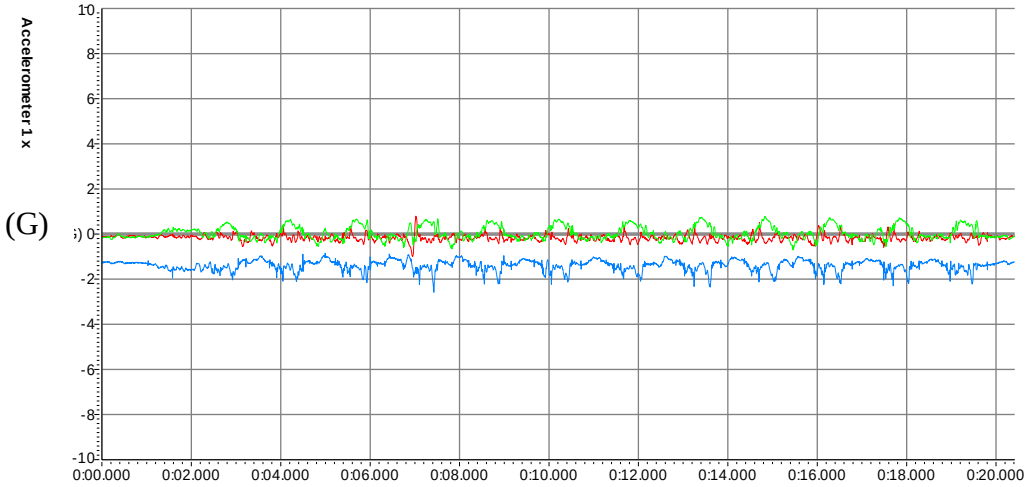


Figure 22: example vibration response as recorded by the patella accelerometer (x, y and z axes) taken from the flexion/extension swing motion protocol of subject 02 right knee first trace.

The above example (figure 22) serves to illustrate the point that the vibration response from the knee is variable in nature and that no clear definition exists with regards to the aforementioned flexion/extension sequence, possibly a series of troughs and peaks can be discerned in the vibration response roughly corresponding to the associated angular trace (figure 21) but there is no definitive repeatable sequence within the recorded response.

When combined the raw data traces presented in the following formats, examples of which are shown below for illustrative purposes. Note that the following three examples (figures 23, 24 and 25) show a ‘live’ trace and that only the accelerometer data trace Y axis is expressed in terms of G, the angular data is superimposed for comparative purposes. The datalog software allowed each individual trace to be selected in which case the angular data was then expressed as angular degrees.

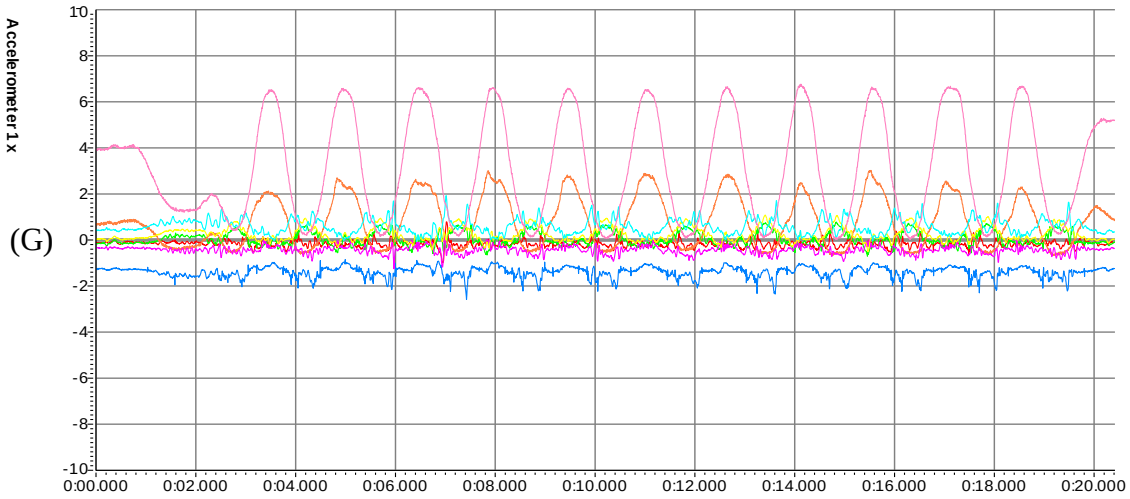


Figure 23. An example of a raw data trace (angular and vibration responses combined) as taken from the swing (unloaded) protocol of subject 02 right knee first trace.

The above example (Figure 23) taken from a normal/healthy knee group participant (subject 02) shows the swing (unloaded) trace from the first motion of this type. As can be seen the trace shows clear definition of the flexion/extension transition point in the angular trace. This meant that in the subsequent processing of the data provided a clear set of angular transition points and thus a set of on average 10-12 flexion extension sequences.

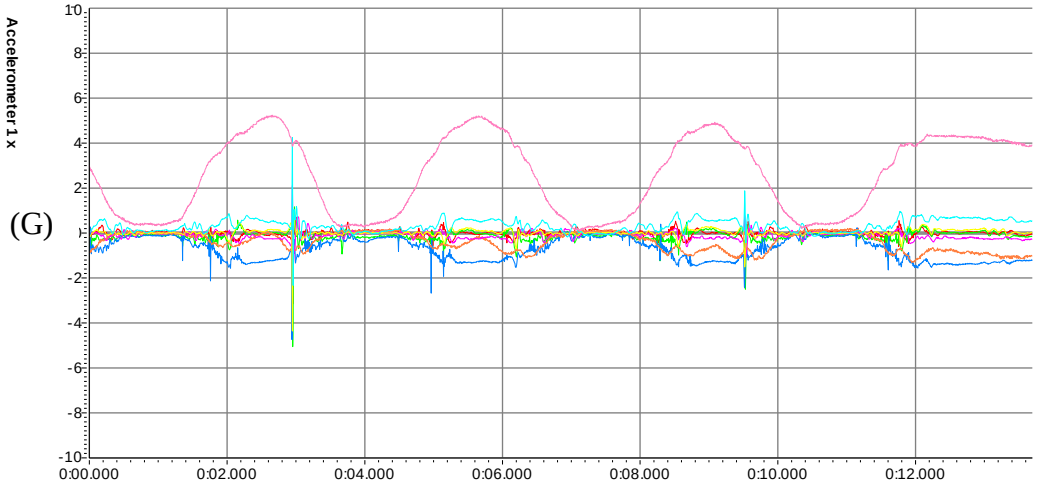


Figure 24. An example of raw data trace taken from the sitting/rising motion protocol of subject 02 right knee first trace.

The example (figure 24) taken from a normal/healthy knee group participant (subject 02) shows the sitting/rising (loaded) trace from the first motion of this type. As can be seen the trace shows a relatively well defined flexion/extension transition point in the angular trace. . This provided a well defined set of angular transition points for the software to identify (on average) 2-3 individual flexion/extension sequences. This was as expected from this part of the protocol but it should be borne in mind that the sample numbers for this part of the protocol will be less than that for the swing (unloaded) protocol. These sequences also were longer in terms of the angular range covered than for the previously shown swing (unloaded) trace.

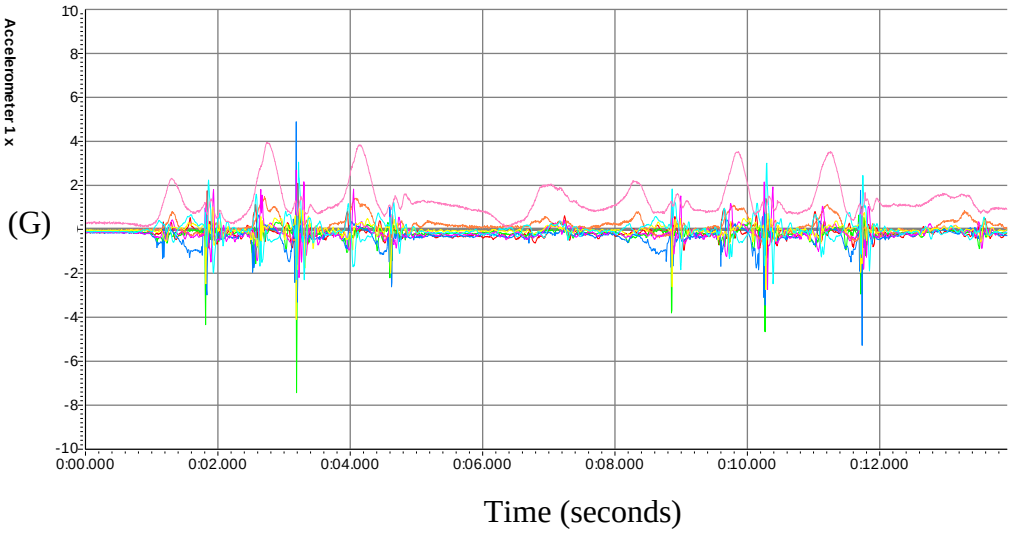


Figure 25. An example of a raw data trace taken from the walking (loaded) protocol of subject 02 right knee first trace.

The above example (figure 25) taken from a normal/healthy knee group participant (subject 02) shows the walking (loaded) trace from the first motion of this type. The trace shows a poor definition of the flexion/extension transition points in the angular trace. This resulted in the subsequent processing of the data being provided with a poorly defined set of flexion/extension transition points for the software and thus a set of flexion extension sequences in the (on average) 5-6 range. It was expected that as ten steps were taken for this part of the protocol that there would be (on average) 10 flexion/extension sequences. These flexion/extension sequences were also shorter in terms of the angular range covered than for the previously shown swing (unloaded) protocol. The number of

flexion/extension sequences also fluctuated by a greater amount in this motion type than found for the swing (unloaded) and sitting/rising (loaded) protocols raw data.

4.24: Sampling Rate Change.

Initially data were collected at a 100 Hz sampling rate as this was used in the previous development of the phonoarthrometer (Abbott 2008). However early on in the data collection phase it was identified that there was a problem with this sampling rate.

The data collected at 100 Hz showed large gaps in the angular range, these gaps correspond to where several degrees of arc of angular motion are covered in the 100^{th} of a second "snapshot" that this sampling rate allows. This is an anticipated occurrence and the phonoarthrometer software was designed to be able to patch these gaps by giving a prediction of up to three degrees of arc. In effect since the knee must have traveled through the angular range between these gaps the software extrapolates the data through the two recorded points, whilst this is acceptable for missing data points up to three degrees of arc any extrapolation for missing angular data greater than three degrees allows for a level of false construction to enter into the data.

As an example where the data is recorded as jumping from 30° to 32° then obviously the angular range must have passed through 31° but where the angular data jumps from 30°to 35° it must have traveled through the intervening degrees but whether or not this is a straight line relationship is unclear.

In the initial data collected at the 100 Hz sampling rate, gaps of up to six degrees of motion were occasionally appearing. Although the software could have been modified to patch these gaps, which would have entailed a significant amount of prediction by the software, it was considered that this might lead to a false representation of the way in which the joint was moving.

On considering what these gaps were suggesting, it at first seemed incredible, as it implied that the knee joint was moving at a rate of six hundred degrees per second across some angular ranges. An error relating to the equipment was suspected of introducing an artifact into the measurement and so the hardware was visually inspected for damage. Repeat tests were then carried by taking further knee joint vibration signal recordings

from the participants that exhibited the gaps in their original recordings. These were carried out at a variety of sampling rates, most notably at 200, 500 and 1000 Hz. These repeat recordings of the knee joint vibration responses showed that the observed gaps were occurring across the sampling rate range and that they were correlated to the sampling rate. For instance, if gaps of six degrees were seen in the 100 Hz data then the gaps were reduced to 3 degrees in the 200 Hz data and therefore they were not an artifact of the hardware sensors.

Consideration was given to why these gaps were not encountered by Abbott (2008) during the initial developmental phase of the phonoarthrometer. This testing was conducted at 100 Hz and no gaps in the angular range above three degrees were observed. One credible explanation is that participants using the wireless system were given more freedom of movement and thus moved their legs at a faster rate than whilst connected to the wired system.

It still however can be seen as an incredible rate of movement in the knee joint and at this time no real viable answer is forthcoming.

In order to continue with the effective collection of data the early raw data was archived and a new set of collected raw data started, this was collected at a sampling rate of 200 Hz and all subsequent data was collected at this rate.

This in effect meant that the phonoarthrometer was gathering information in the raw data at double the rate that what the original prototype was designed to handle. Apart from increasing processing times needed by the software to handle the added information, it appeared to have no obvious affect on the operation of the software. A full and careful consideration of this increase would be wise in the development of any future versions of the phonoarthrometer.

4.25: The Zeroing process.

The data collection protocol includes a zeroing process for the angular trace this is explained in the previous chapter (3) and is carried out prior to starting each test protocol. The purpose of this zeroing of the angular trace is to provide an equalised starting point for the gathering of all participant data.

This process sets the beginning of the angular trace to zero degrees that should in theory provide an indication of a fully extended leg and give a standardised point from which angular measurements can be taken. This starting point of full extension is achievable for participants with healthy knees, but whilst collecting data from osteoarthritic knee joints it was noted that a number of participants had decreased range of angular flexibility in their knee joint and could not extend the knee below 20 degrees.

If the knee must be zeroed whilst the knee is not in full extension the start point for this data will not be the same as for fully extended knees. In effect it means the start point for collecting angular data's from a wide range of participants is not effectively standardised. This in effect means that whilst some participants' knees (usually normal knee joints) will be starting at an effective zero degrees of flexion/extension others (those from the osteoarthritic group with reduced range of movement) will be recorded as starting at zero degrees but in actuality be starting from, for instance, 20 degrees of flexion/extension.

This is an important point to note because in the previous development of the phonoarthrometer (Abbott, 2008) all knee joints used for testing were able to straighten adequately and therefore this problem with zeroing of the angular trace was not identified.

If the knee is not zeroed at a consistent point the further measurements taken will be of dubious validity since the angular position data for all collected data would be inconsistent. This is not as great a problem as first might be thought as the data is not dependant on angular position for comparison of results.

4.3: Data processing.

The data processing phase consisted of using the phonoarthrometer software to analyse the collected data.

4.31: Data processing realities.

In general data from the swing (unloaded) protocol provided the most reliable data for processing. This data was the most consistently processed data that ran without any

obvious problems and produced a good number of flexion/extension segments per raw data trace for subsequent analysis.

The walking (loaded) and sitting (loaded) data groups were less consistent in terms of the level of data that was able to be fully processed by the phonoarthrometer software. This can be seen in both the osteoarthritic affected and healthy/normal groups.

The ability of the software to process the raw vibration response data seemed to be dependant on how clearly defined the sequence of angular data points required for the identification of the transition between flexion and extension sequences were. These sequences act as the "chopping points" that the software uses to define the flexion/extension sequences for subsequent processing.

On many of the walking/sitting (loaded) data files these sequences appear to be poorly defined, as the software had difficultly in clearly identifying the change between flexion/extension sequences. As a consequence of this effect many files of the raw data would not fully process with viable results. This lead to a (relatively) low amount of viable processed data for many of the participants when it came to the walking/sitting (loaded) protocols.

4.4: Building the micro-structure library.

The phonoarthrometer requires a database of microstructure motions for its prediction output to be calculated.

In order to do this data was taken from normal knee joints. These vibration signal responses were inputted into the phonoarthrometer and stored in the microstructure library (database). The training group for this purpose was carefully identified from selected normal/healthy knee joint participants. At this point the decision as to which data to include in this training group had to be very carefully considered due to the fact that entering an abnormal response would skew later predictions. Adding a microstructure motion subtype to the database from an abnormal knee would be interpreted by the system as a normal motion type and lead to future identification of this abnormal response as normal. The process of teaching the software artificial intelligence (AI) to recognise

distinct groups from one another is the accepted means of training a neural network to behave in the correct manner (Zhang et al, 1990).

If the data entered looked acceptable as a normal response in that it didn't radically deviate when compared to the previously entered responses when run through the system, then it was saved in the core microstructure library and used by the system in the production of future output prediction charts. Radically different responses were not initially entered into the system but were held for future comparison as the microstructure library grew. They were then reassessed later in the process by which time they might be closer to the data already entered in which case they were included in the microstructure library. Self evidently, the first data shown to the system could not be compared to previous data in the database and therefore it was chosen from the raw data based on an assessment of the biometric data supplied by the participant. The process of carefully adding to the database continued throughout the training phase until the system was deemed to have stabilised. The chart below (figure 26) represents how the system stabilised. The numbers of files in the microstructure library increases as new files are entered into the system. As this continues fewer and fewer files are found to add to the microstructure library containing new data associated with a normal response. The curve eventually reaches a plateau indicating that no more microstructure types are being found for storage in the microstructure library. At this point the system is described as having "stabilised".

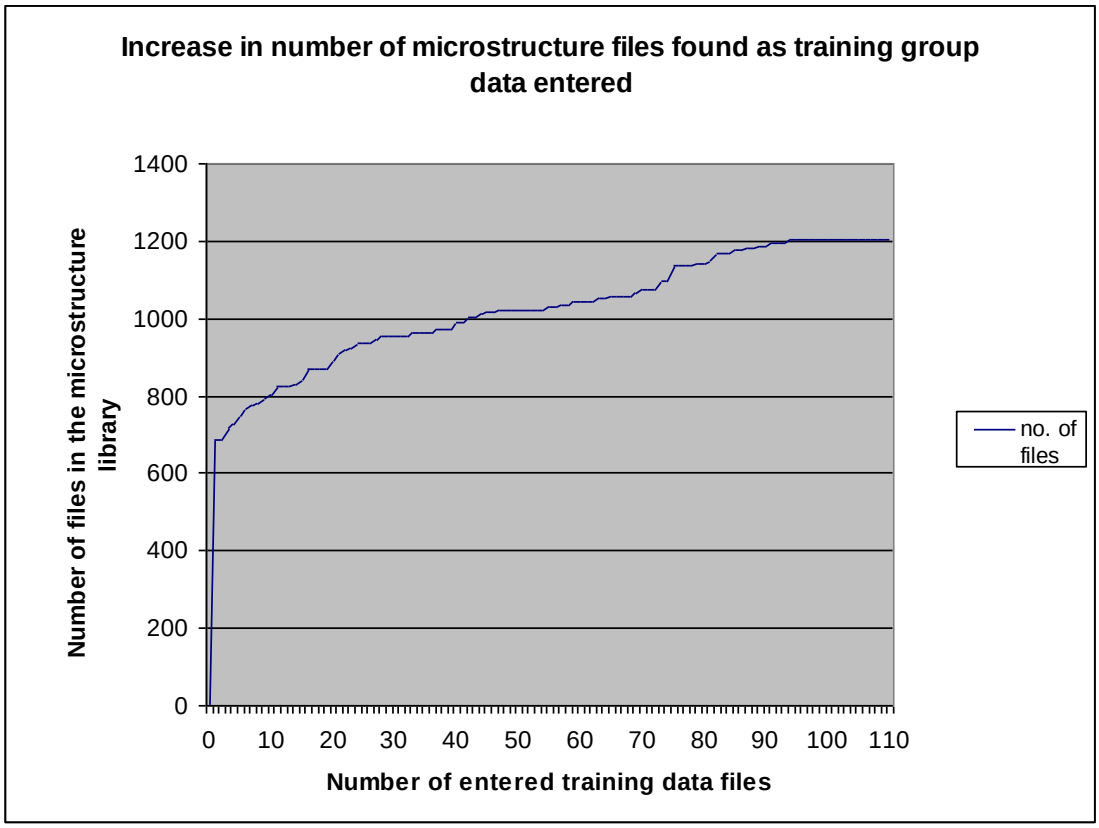


Figure 26. Increase in the number of microstructure files recorded by the microstructure library.

The above graph (figure 26) shows the number of microstructure motion files recorded in the microstructure library in relation to the number of individual files of raw data entered into it. The increase in discovered files increases rapidly over the first number of files entered, this gradually levels off once 80-90 individual raw data files have been entered. This is due to a gradual stabilisation of the microstructure library as fewer new microstructure types are identified in each subsequently inputted vibration response data file. By the time 94 individual raw vibration response data files have been inputted the microstructure has reached 1203 files and after this shows no new microstructure types being found for the next 16 files entered. At this stage the microstructure library was deemed to be sufficiently stabilised and was locked for use in all subsequent processing of data.

This does not mean that all microstructure types have been discovered but rather that the probability of a file containing a new type has dramatically decreased to a point where it

can be considered that less than one percent of subsequently processed files will contain a previously unseen microscale motion type.

The final microstructure library was constructed from the raw vibration response data taken from 22 knee joints. All participants were from the healthy/normal knee joint group. In total 2250 individual flexion/extension sequences were entered to produce the final microstructure library used in processing of all subsequent data.
The final microstructure library contained a total of 1203 individual microscale type files and occupied a computer disc space of 44.9 Mb.

This final microstructure library it should be noted was constructed from only flexion and extension motion types of the swing (unloaded) protocol. It was deemed unnecessary to construct separate microstructure libraries for each of the other two motion protocol types (sitting/rising and walking). The reasoning behind this being that the knee joint should only be able to move in a finite number of ways and it was theorised that these would have been discovered from the swing motion (unloaded) protocol data alone. Indeed if walking and sitting/rising (loaded) data provided further undiscovered motion types these would have noticeably been shown by a rapid increase in the number of microscale motion files following processing of data from these protocol types. This was not the case; the microstructure library remained stabilised whilst processing the walking and sitting/rising (loaded) protocol motion data. This suggests that all the required microscale motion types were already available in the microstructure library to enable construction of the prediction output.

For future reference and when time permits it would be instructive to continue this training process not only for the swing (unloaded) data but also for the walking and sitting/rising (loaded) data as well. The purpose being in order to create specific microstructure motion libraries for these protocols and to assess the data from the sitting/rising and walking (loaded) protocol groups to see any affect this has on the processed results.

4.5: Preliminary experiment with sensor location.

4.51: Introduction

The generation and transmission of sound through the knee joint, as previously discussed, suggests that the vibration signal recorded will be variable dependent on where it is collected from on the surface of the knee. This section is concerned with the experimental testing of variation in the recorded vibration signal caused by transposing the placement of the accelerometers around the selected anatomical landmarks (centre of patella and centre medial joint line). This research is of key concern, as to date this has never been reported in the existing literature and represents a significant deficiency regarding how the placement positions are determined for the accelerometers upon the knee.

In order to test this, an experimental protocol was developed that involved altering the placement of the accelerometer sensors around the knee joint's anatomical landmarks that were previously identified as attachment locations. The methodology of this preliminary experiment and placement locations of the accelerometers has been discussed previously (chapter 3).

It can be theorized that in line with the hypothesises derived in chapter 2 relating to the propagation and transmission of sounds through both solids (such as bone) and liquids (such as the synovial fluid) and the effects on sound transmission found at the interface of these two states as well as the focusing/ dispersion effects found within different shaped solids (for instance at corners) that accurate repeatable placement of the accelerometer sensors will be of vital importance if the vibration signal is to be recorded consistently in a dynamic joint such as the knee.

It should be borne in mind that the vibration signal from the knee is not what is being tested here, the signal if it were possible to collect it at source within the knee, without the transmission pathway through the knee, then this would be the same. It is the transmission pathway that alters the signal and introduces a level of variability.

The literature previously reviewed shows no apparent concern with regard to any limitations placed upon the collection of the vibration signal relating to placement position of the accelerometer. It would seem that previous research in this field has not identified this as a potential source of error. Little mention is made of how the accelerometers are positioned upon the knee joint in existing literature implying that other researchers in this field do not have a strict protocol for placement of the accelerometers.

Existing literature is frequently indistinct as to the exact position that the accelerometers are placed, often simply stating that the accelerometers were used attached to the patella or just on the knee joint (Beverland et al. 1986, Barr et al. 1994) this is not to say that all papers are equally vague, for instance of the better examples from the literature, Krishnan et al. (2001) states, that the accelerometer sensor was affixed at the participant's mid patella, however there is still no indication of a protocol for accurate repeatable placement given.

One possibility why this issue has not been identified in the literature by the Calgary research group is due to their reliance on analysing vibration signals from a historic database. They therefore have never had to consider the practicalities associated with collection of the vibration signal from the knee; in effect there is a level of dissociation from the data source.

As a limitation identified in the existing literature this means that the results presented here show the first attempt a determining whether the placement accuracy of the accelerometers on the knee joint has any effect on the resultant data.

4.52: Results

The following section shows the results obtained from this experiment. All data is from flexion/extension sequences derived from the swing (unloaded) protocol extended as described in chapter 2. The results are grouped by axis for each of the patella and medal line accelerometers, each group shows three figures with displacements for 50%, 100% and extreme followed by a further two figures showing mean % error minimum /maximum and average error minimum/maximum plotted in comparison to values for the

correct (optimal) placement of the accelerometer (shown in darker colours at the centre of the summary graphs). Each of the displacement position figures show the mean value of % error min/max and average error min/max for all flexion extension vibration signal sequences as analysed by the phonoarthrometer software. In each displacement position an illustrative output chart is included these represents one individual flexion/extension sequence and were chosen where possible to be representative of the mean value of all flexion/extension sequences from the data analysed.

For each of the summary graphs showing mean % error and mean average error in comparison to the optimally placed accelerometer, displacements of the patella accelerometer in the vertical plane are given the annotation sup. or inf. corresponding to superior (above) and inferior (below) displacements. Hence 50% sup. refers to the displacement of the patella accelerometer by 50% of the distance from the optimal to the upper edge of the patella. In a similar manner displacements in the horizontal plane are annotated as med. and lat. corresponding to medial (right) and lateral (left) displacements. For the medial line accelerometer the annotations post. and ant refer to posterior (backward) and anterior (forward) displacements.

Error bars are shown for each data point; these represent the standard error of the sample mean. T tests were carried out for each of the displaced accelerometer data points in comparison to the optimally placed values; an annotation of N/S above/below the data point represents a value that was not significantly different from that for the optimally placed accelerometer.

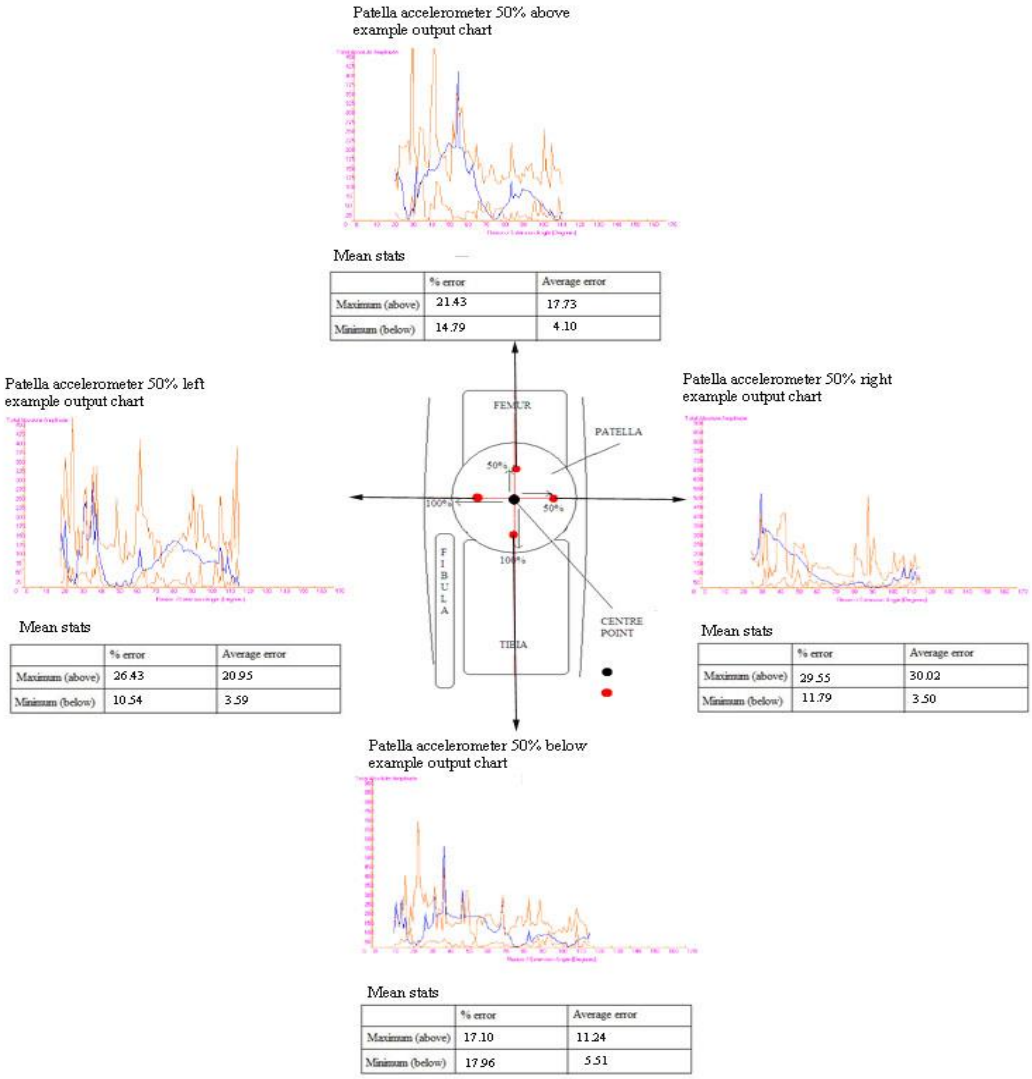
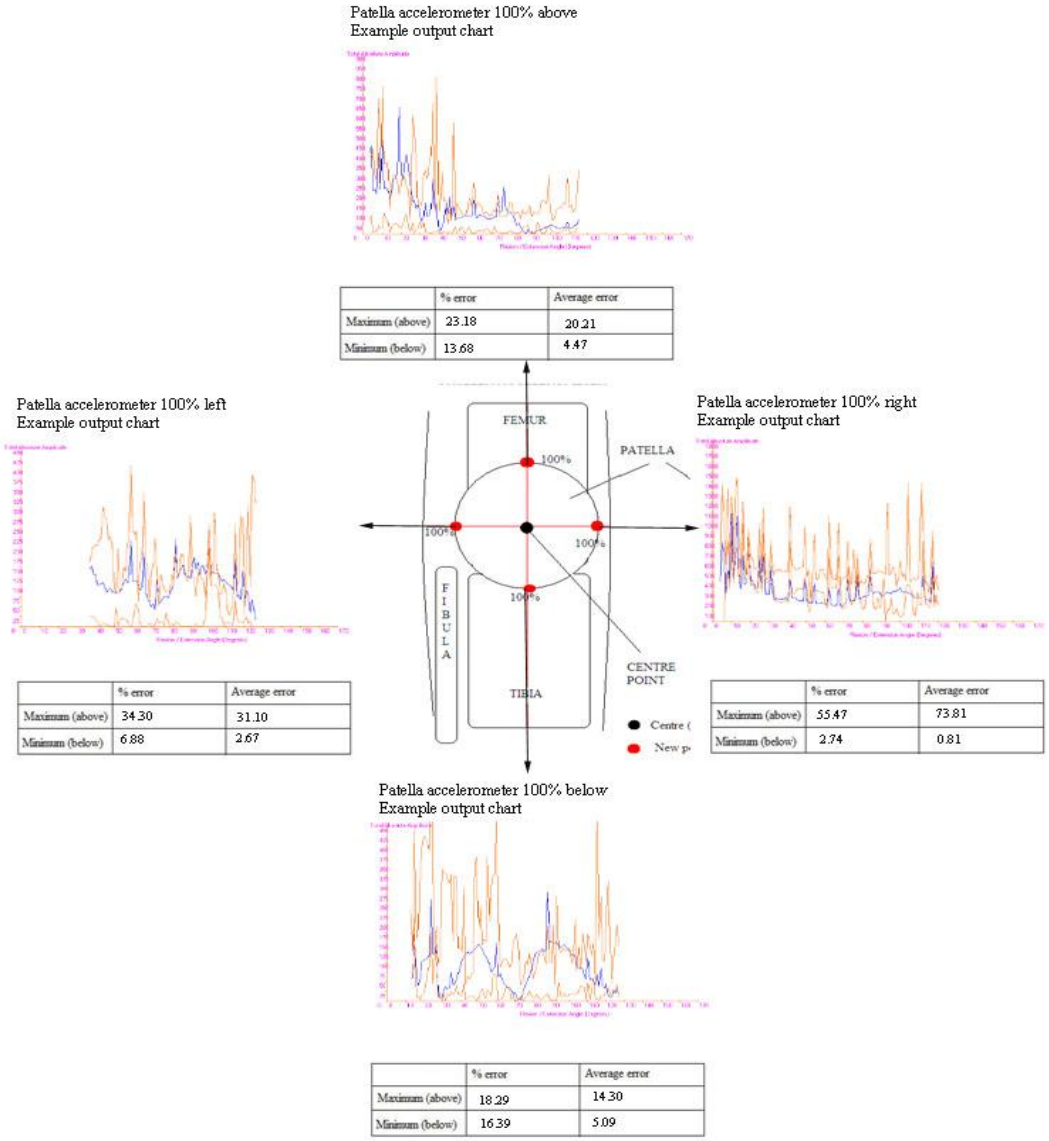


Figure 27. Patella accelerometer 50% displacement – X axis



	% error	Average error
Maximum (above)	23.18	20.21
Minimum (below)	13.68	4.47

	% error	Average error
Maximum (above)	34.30	31.10
Minimum (below)	6.88	2.67

	% error	Average error
Maximum (above)	55.47	73.81
Minimum (below)	2.74	0.81

	% error	Average error
Maximum (above)	18.29	14.30
Minimum (below)	16.39	5.09

Figure 28. Patella accelerometer 100% displacement – X axis

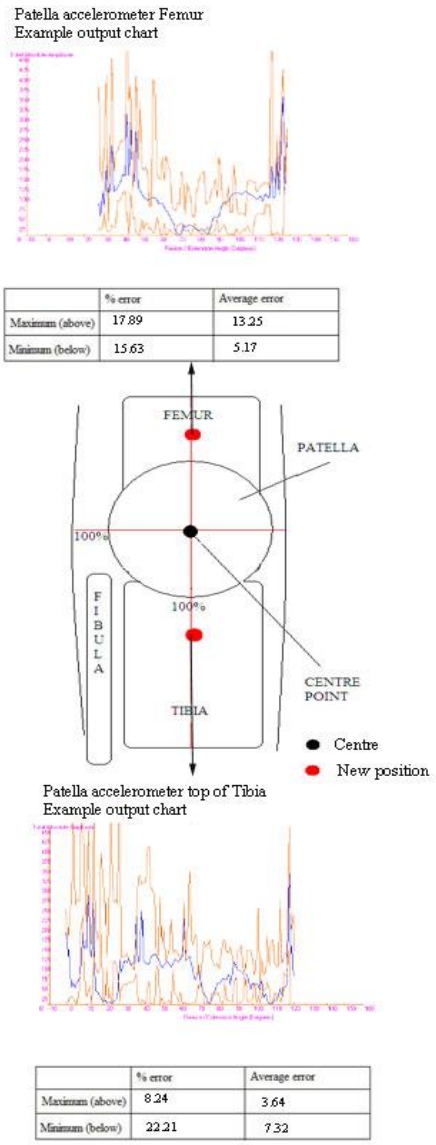


Figure 29. Patella accelerometer extreme displacement – X axis.

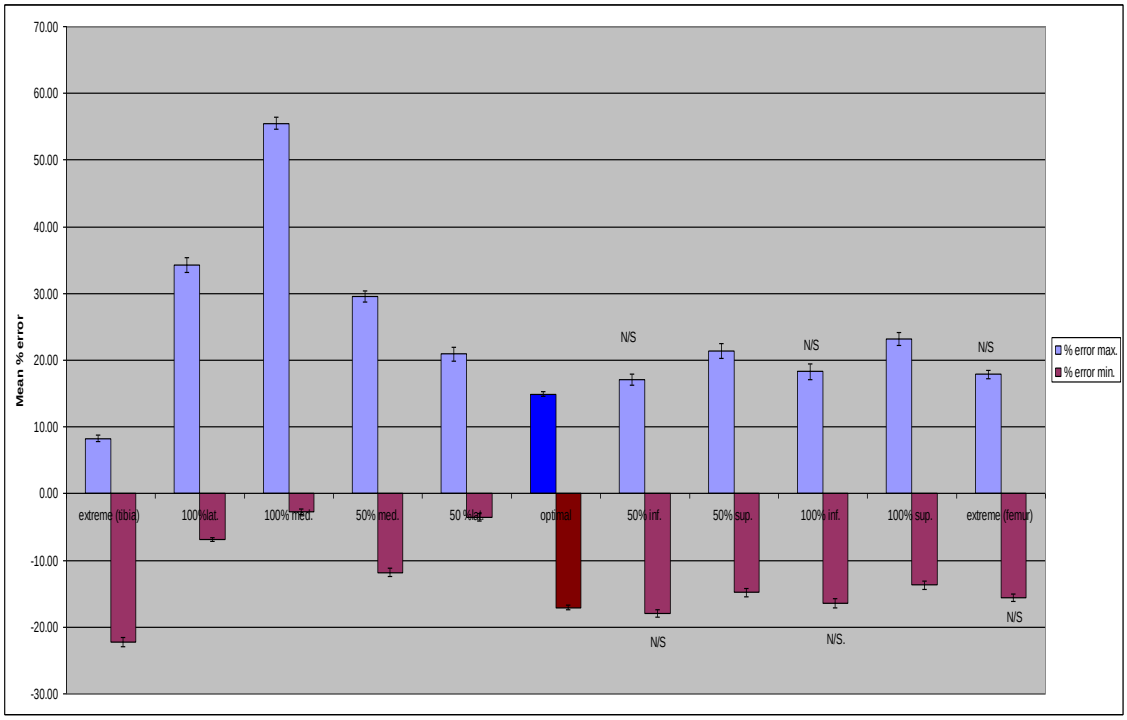


Figure 30. Mean % error maximum and minimum values for the X axis of the patella accelerometer at various displacements around the knee joint.

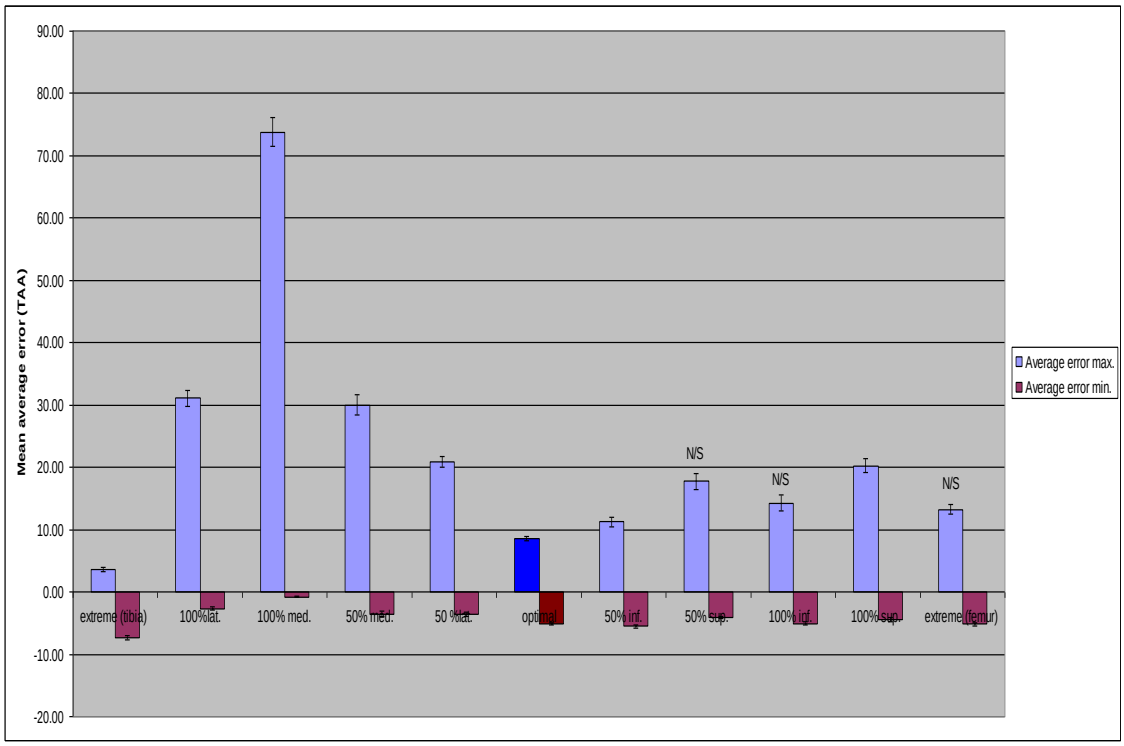


Figure 31. Mean average error maximum and minimum values for the X axis of the patella accelerometer at various displacements around the knee joint.

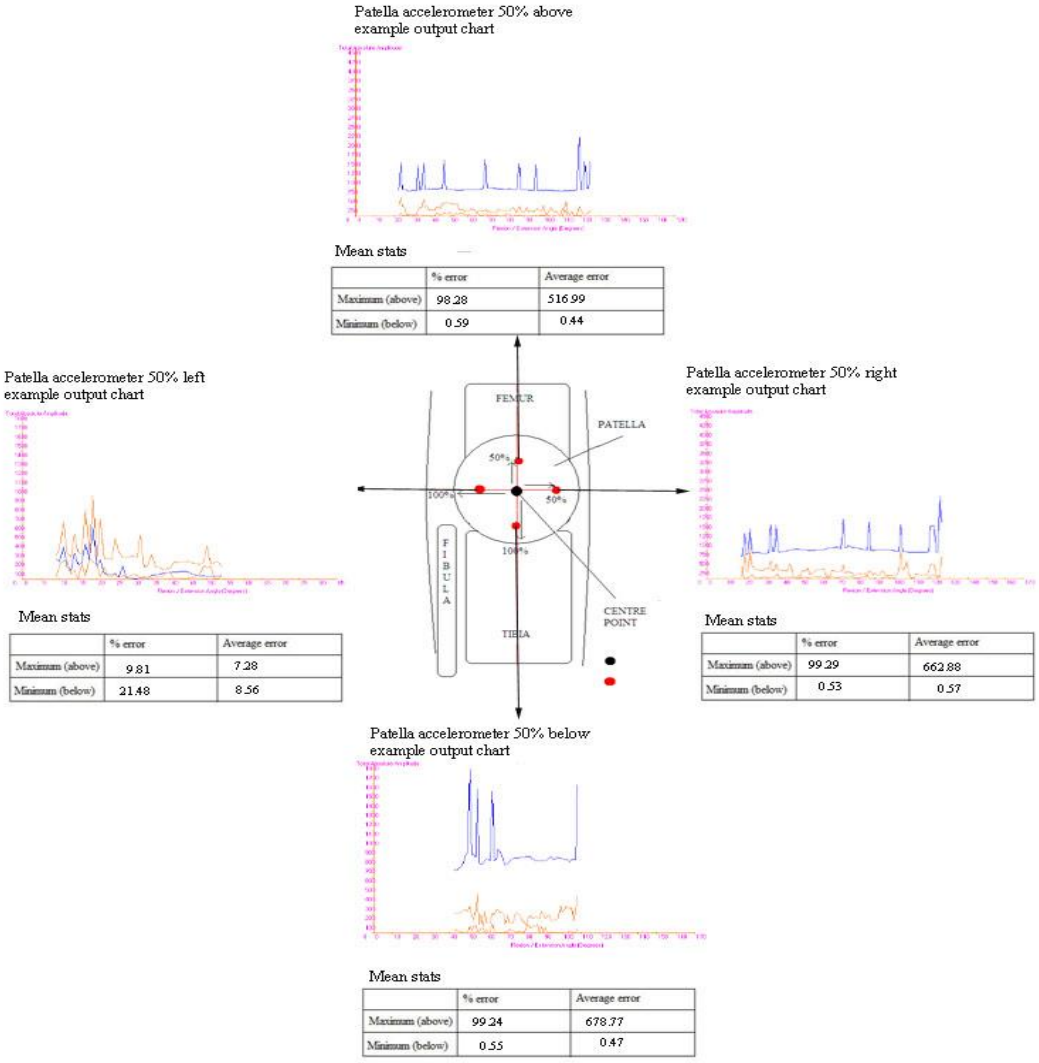


Figure 32. Patella accelerometer 50% displacement – Y axis

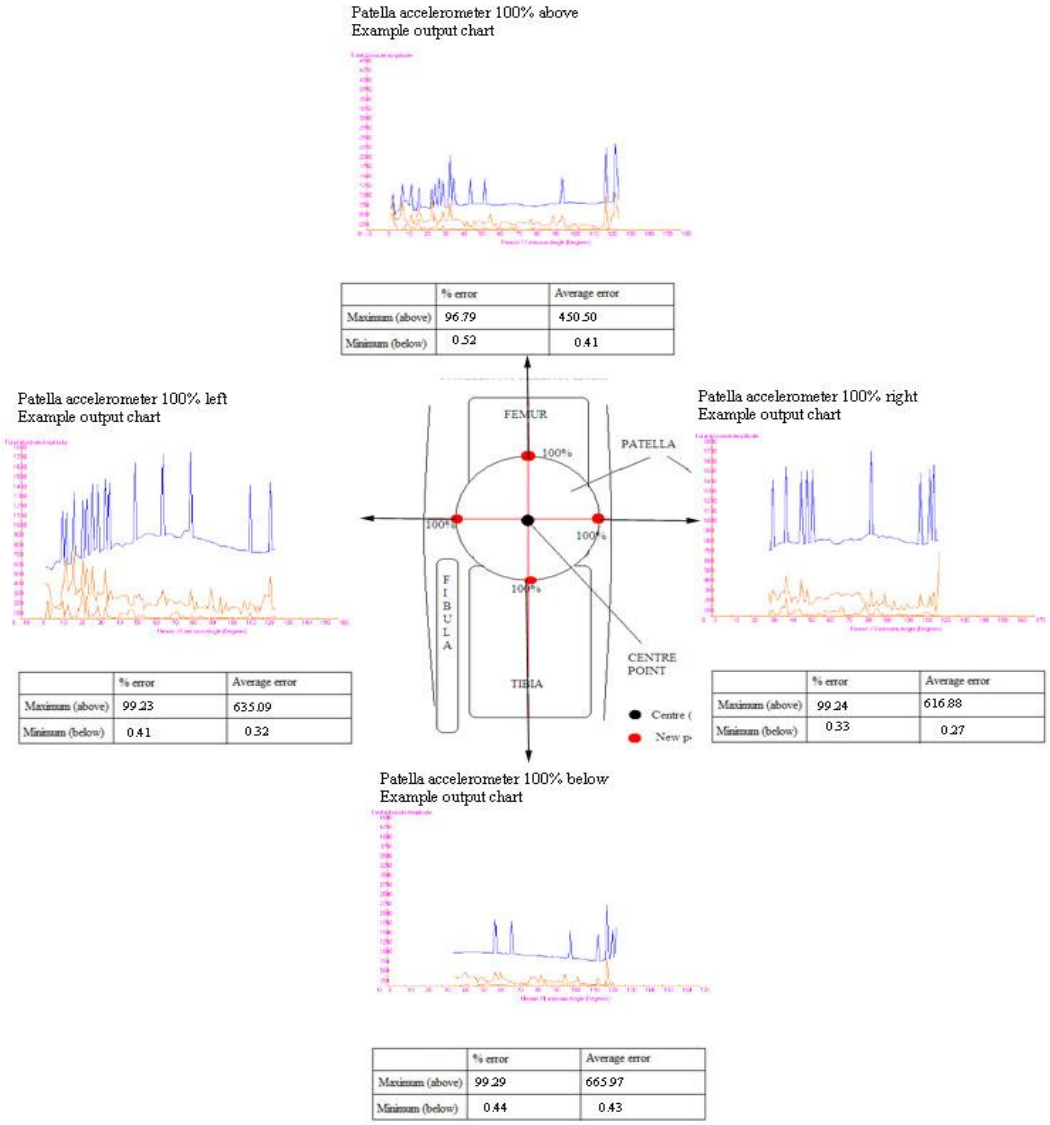


Figure 33. Patella accelerometer 100% displacement – Y axis.

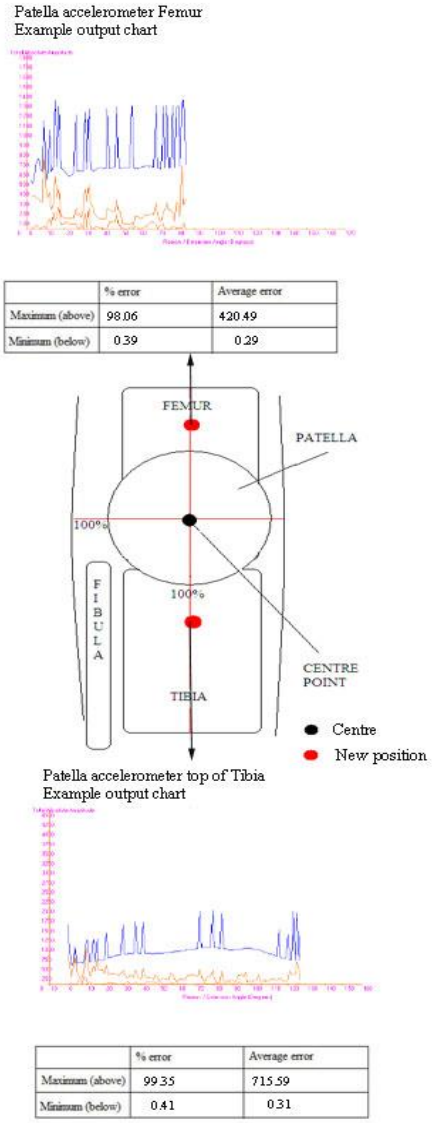


Figure 34. Patella accelerometer extreme displacement – Y axis.

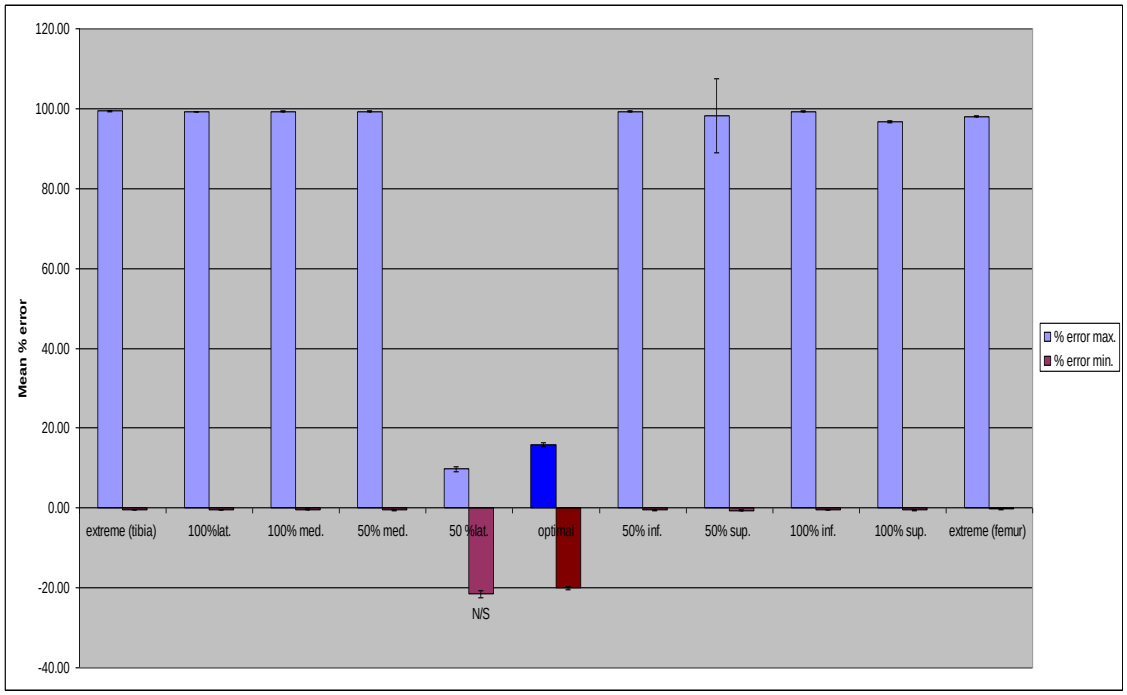


Figure 35. Mean % error maximum and minimum values for the Y axis of the patella accelerometer at various displacements around the knee joint.

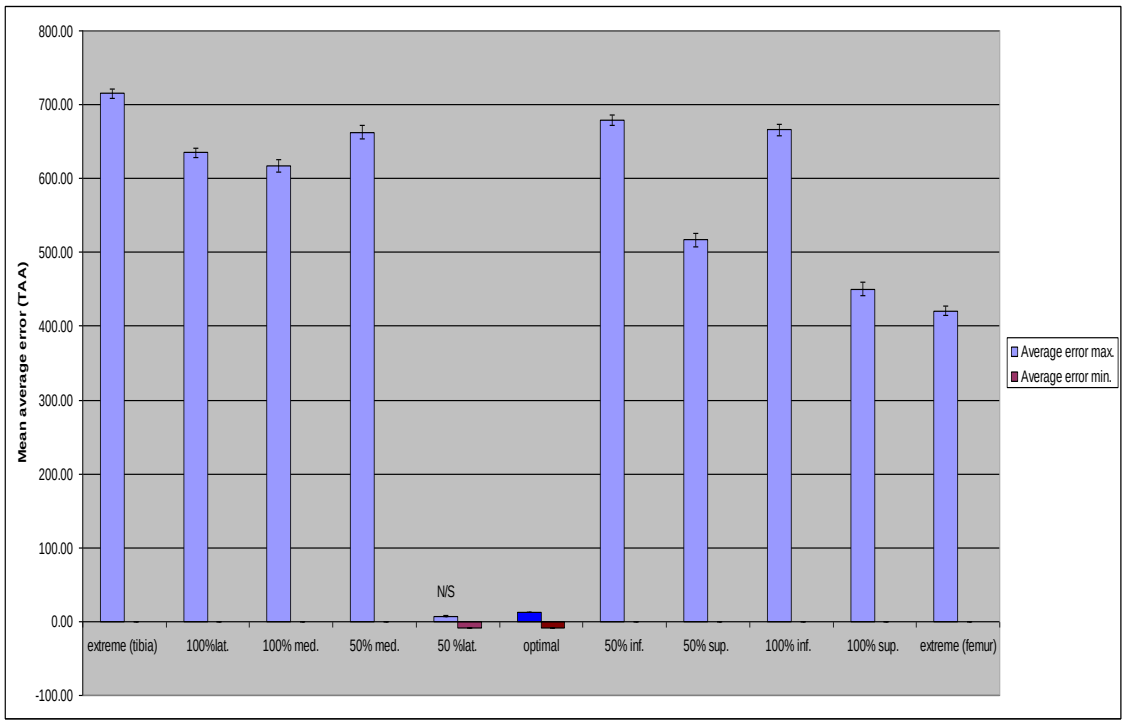


Figure 36. Mean average error maximum and minimum values for the Y axis of the patella accelerometer at various displacements around the knee joint.

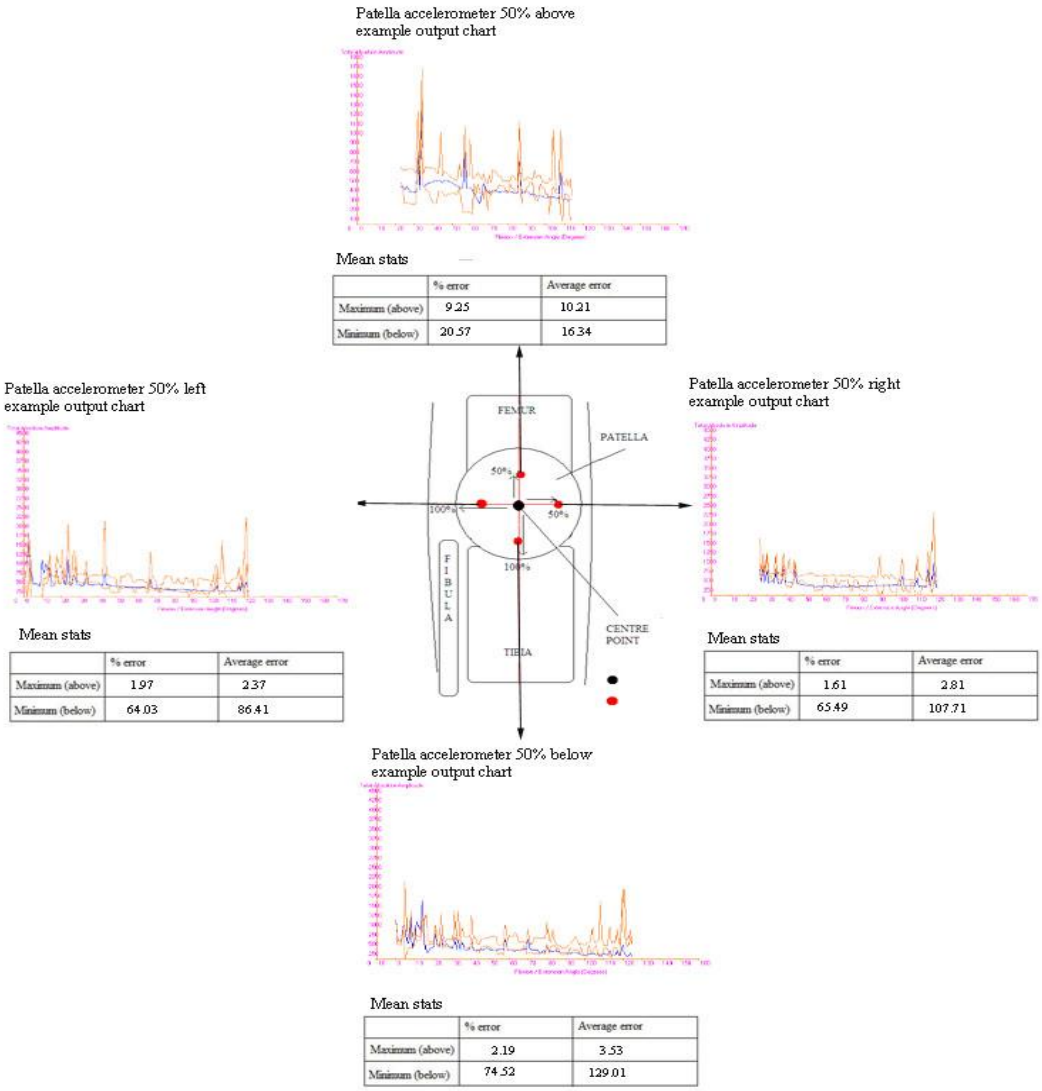
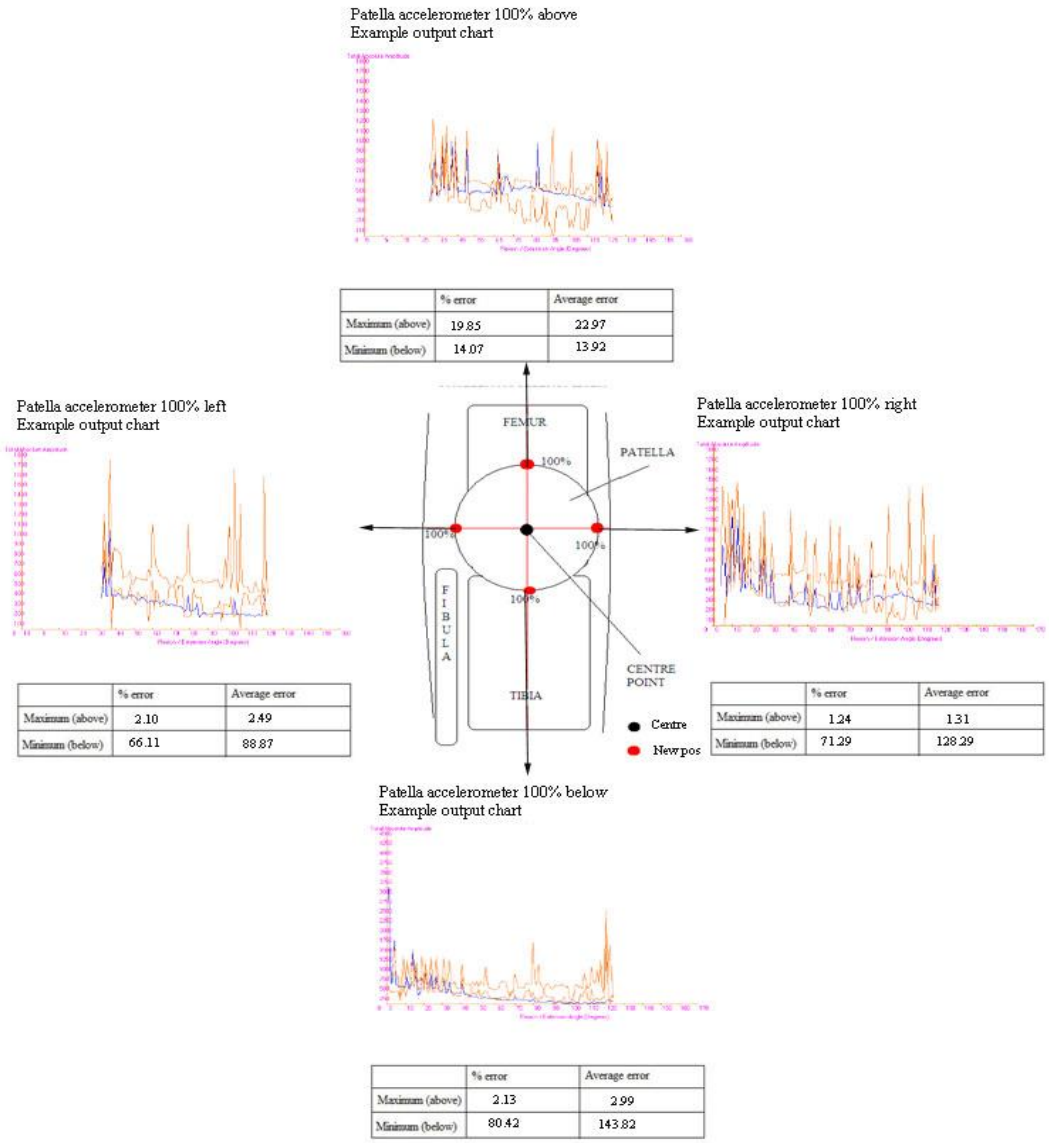


Figure 37. Patella accelerometer 50% displacement – Z axis.



	% error	Average error
Maximum (above)	19.85	22.97
Minimum (below)	14.07	13.92

	% error	Average error
Maximum (above)	2.10	2.49
Minimum (below)	66.11	88.87

	% error	Average error
Maximum (above)	1.24	1.31
Minimum (below)	71.29	128.29

	% error	Average error
Maximum (above)	2.13	2.99
Minimum (below)	80.42	143.82

Figure 38. Patella accelerometer 100% displacement – Z axis

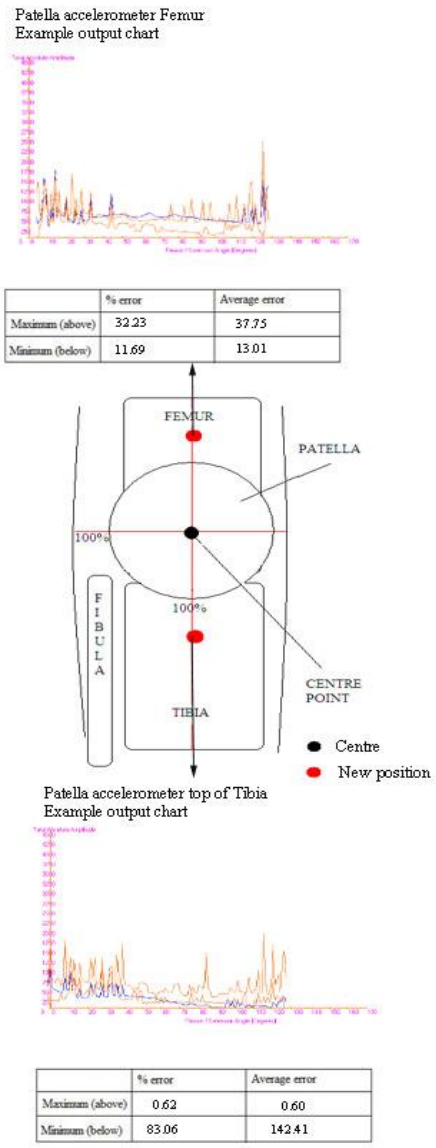


Figure 39. Patella accelerometer extreme displacement – Z axis.

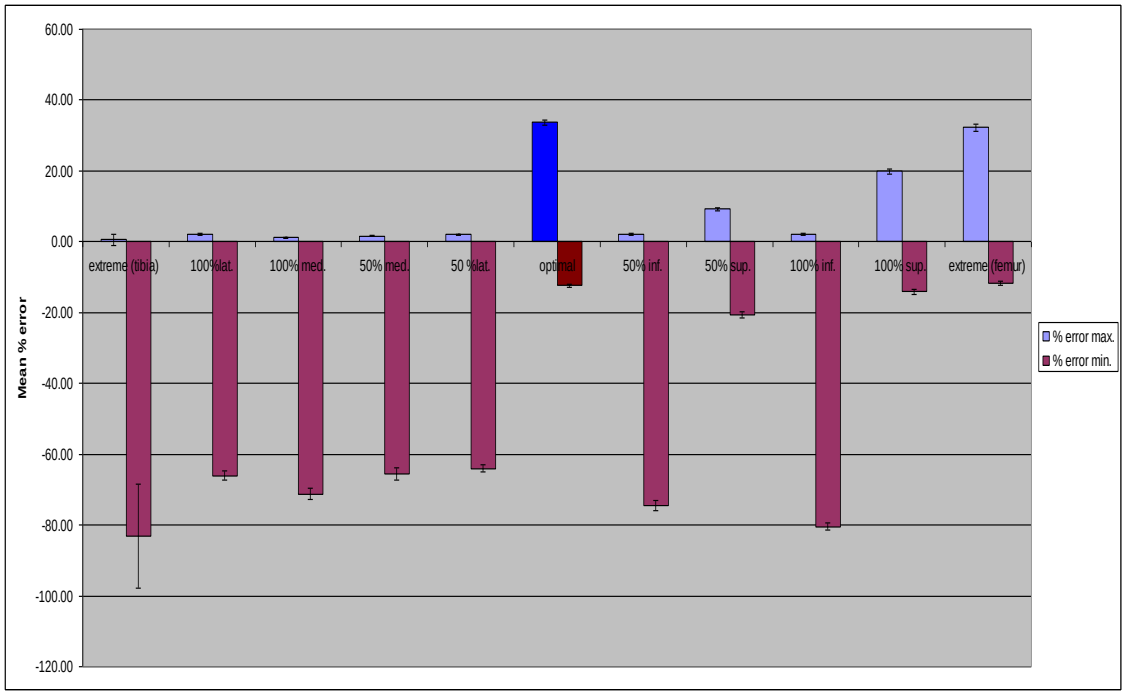


Figure 40. Mean % error maximum and minimum values for the Z axis of the patella accelerometer at various displacements around the knee joint.

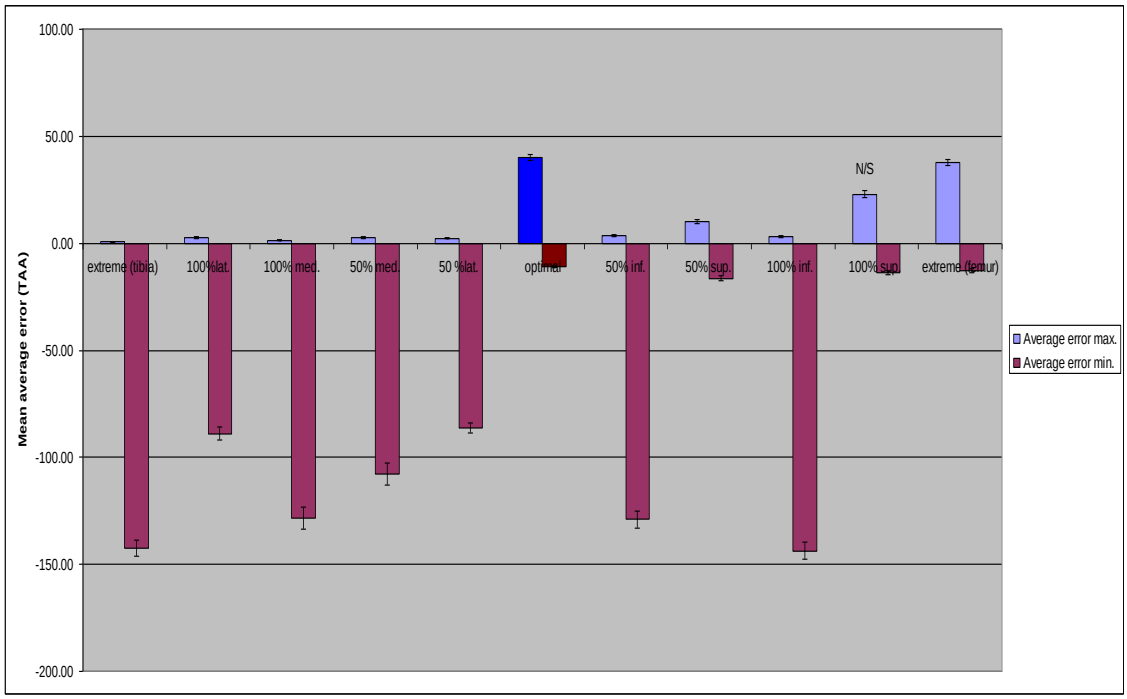


Figure 41. Mean average error maximum and minimum values for the Z axis of the patella accelerometer at various displacements around the knee joint.

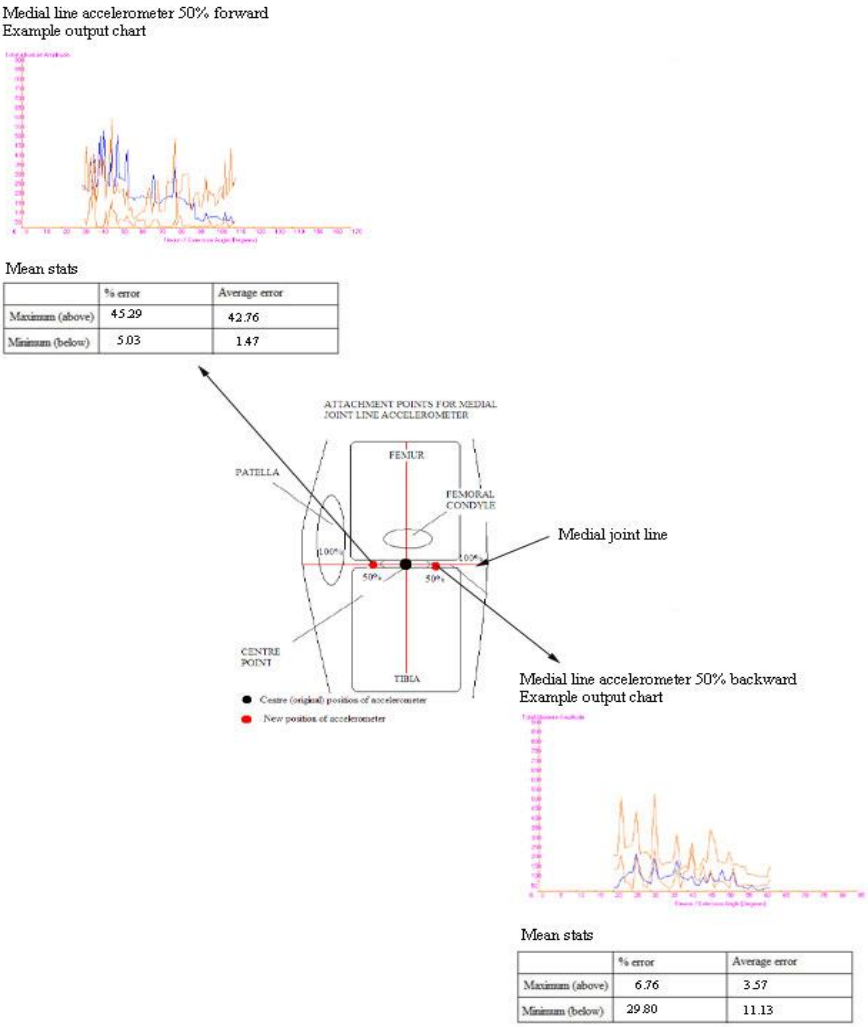


Figure 42. Medial line accelerometer 50% displacement – X axis

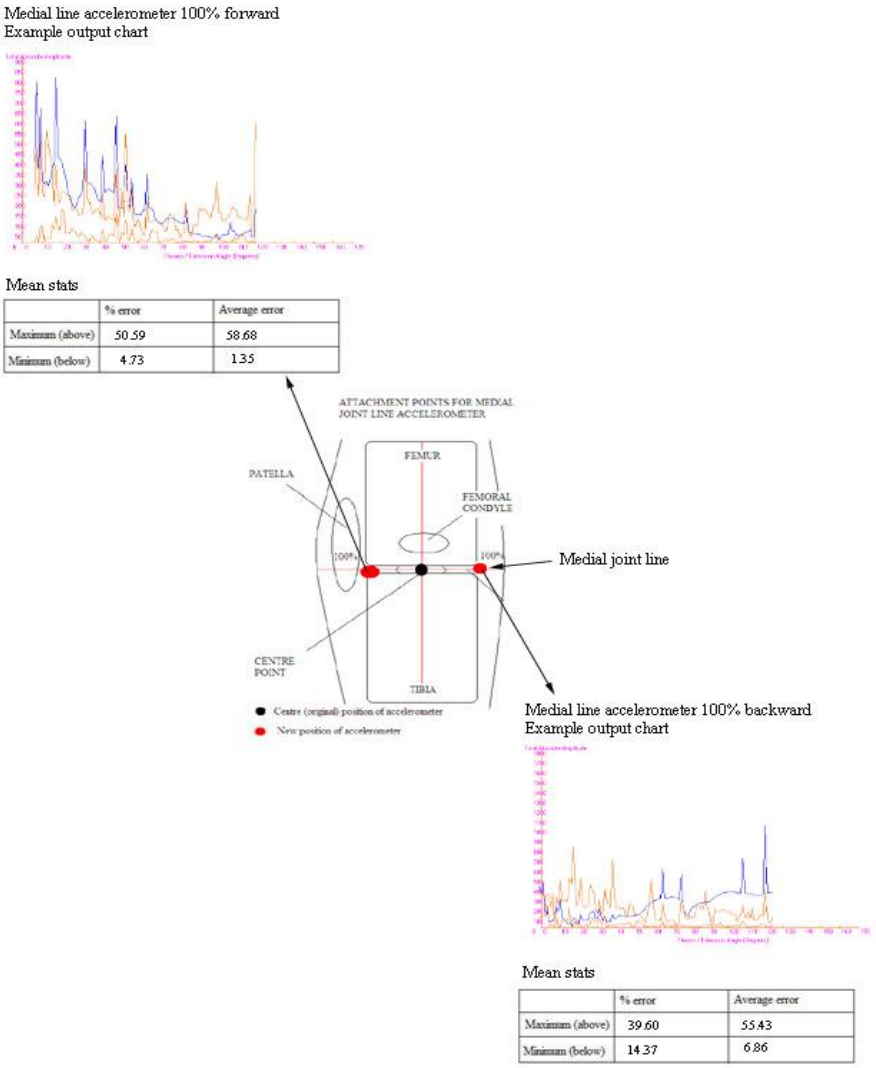


Figure 43. Medial line accelerometer 100% displacement – X axis.

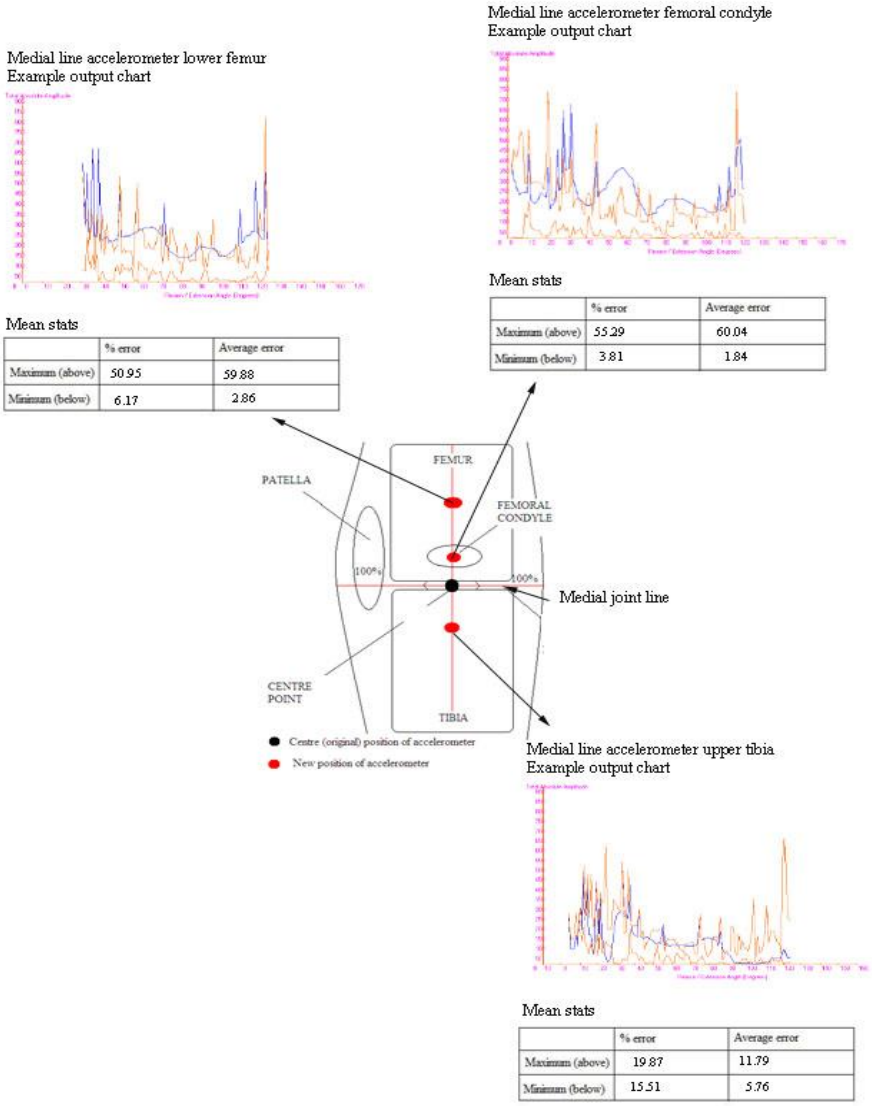


Figure 44. Medial line accelerometer extreme displacement – X axis.

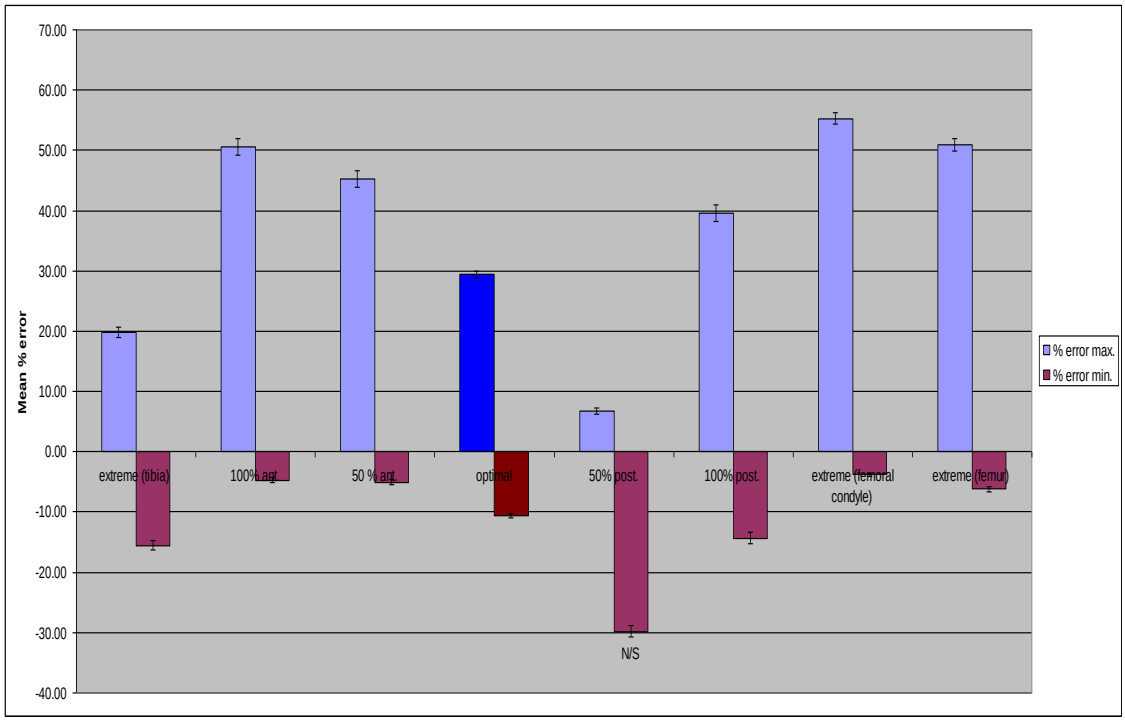


Figure 45. Mean % error maximum and minimum values for the X axis of the medial line accelerometer at various displacements around the knee joint.

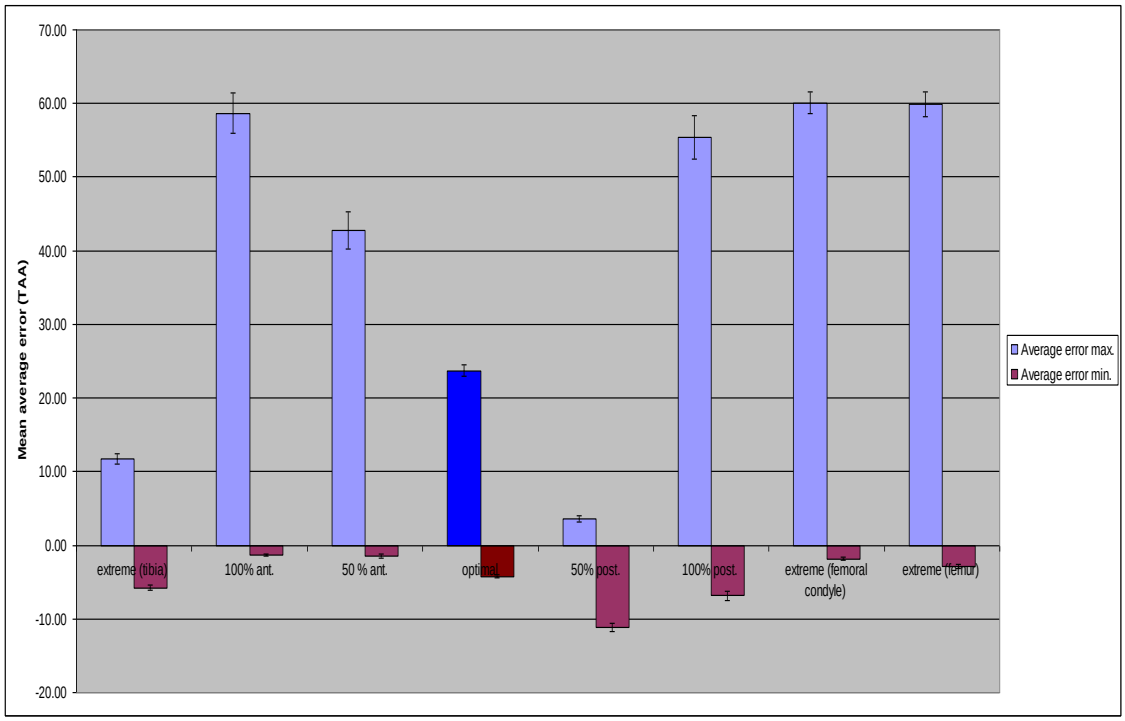


Figure 46. Mean average error maximum and minimum values for the X axis of the medial line accelerometer at various displacements around the knee joint.

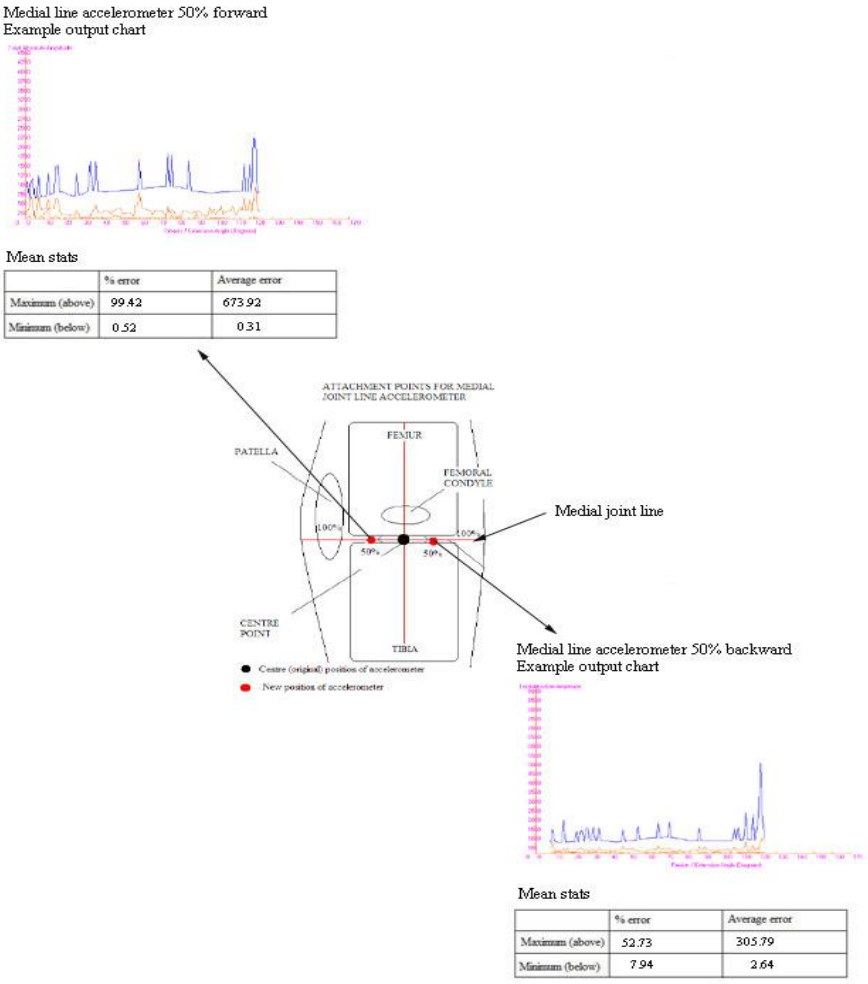


Figure 47. Medial line accelerometer 50% displacement – Y axis.

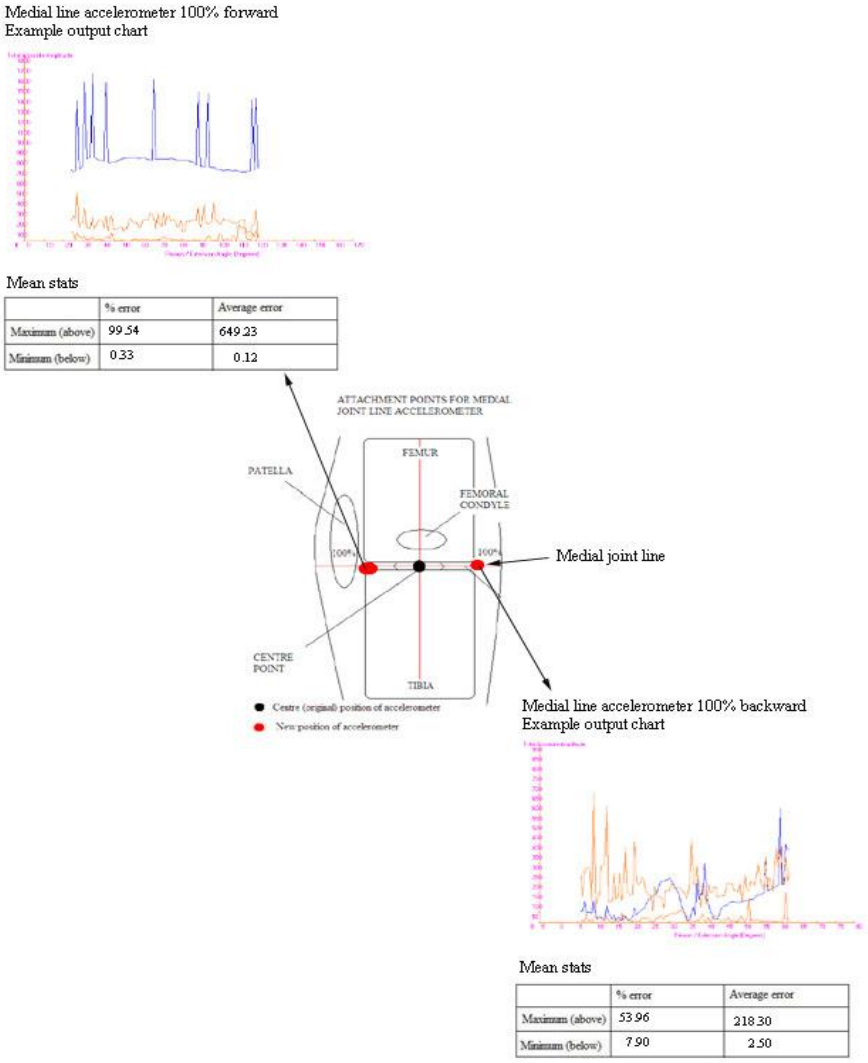


Figure 48. Medial line accelerometer 100% displacement – Y axis.

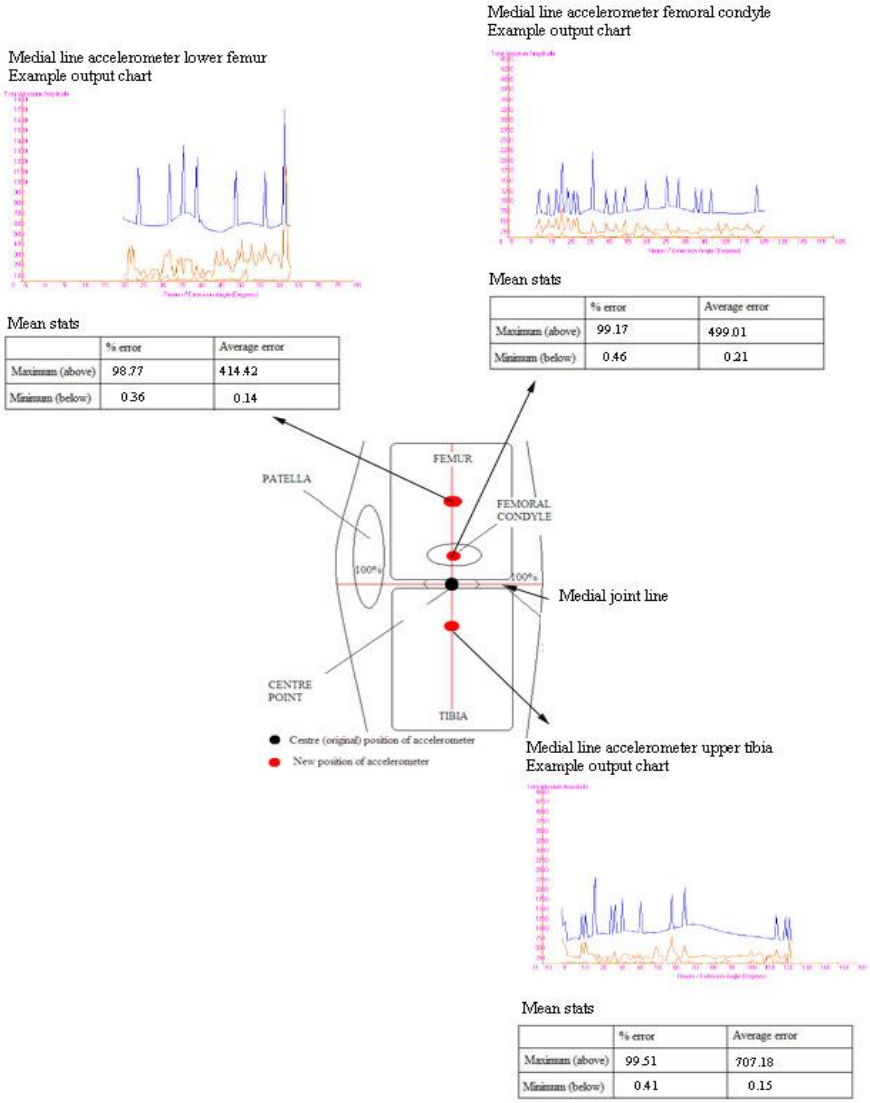


Figure 49. Medial line accelerometer extreme displacement – Y axis.

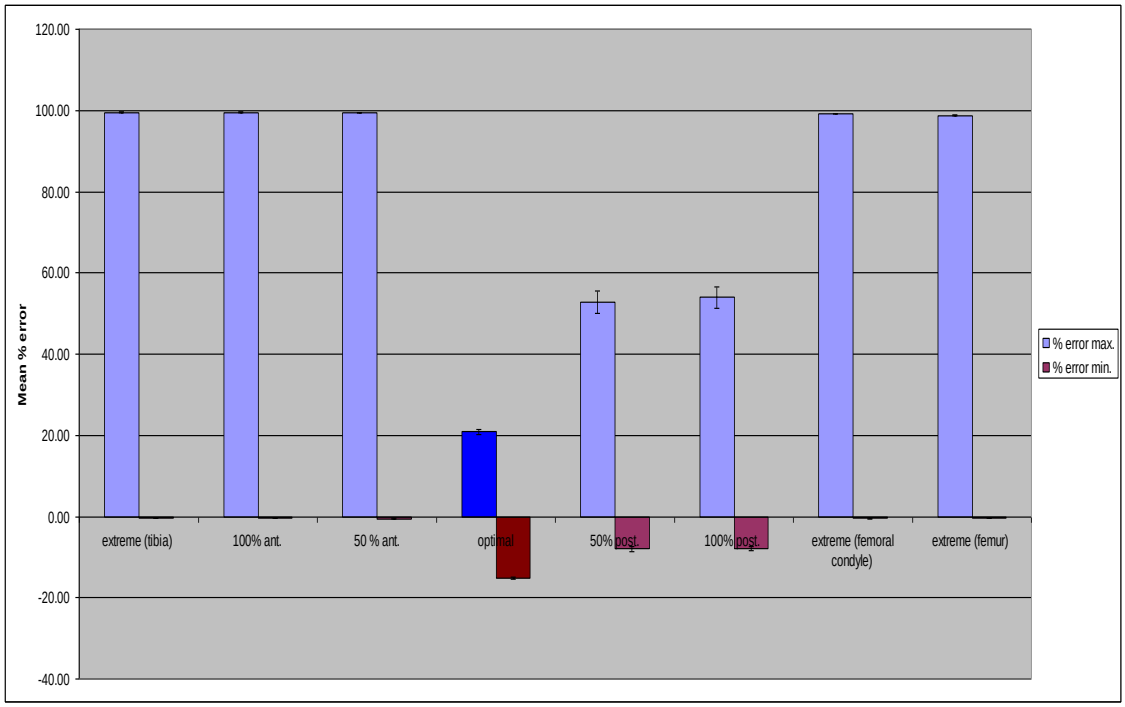


Figure 50. Mean % error maximum and minimum values for the Y axis of the medial line accelerometer at various displacements around the knee joint.

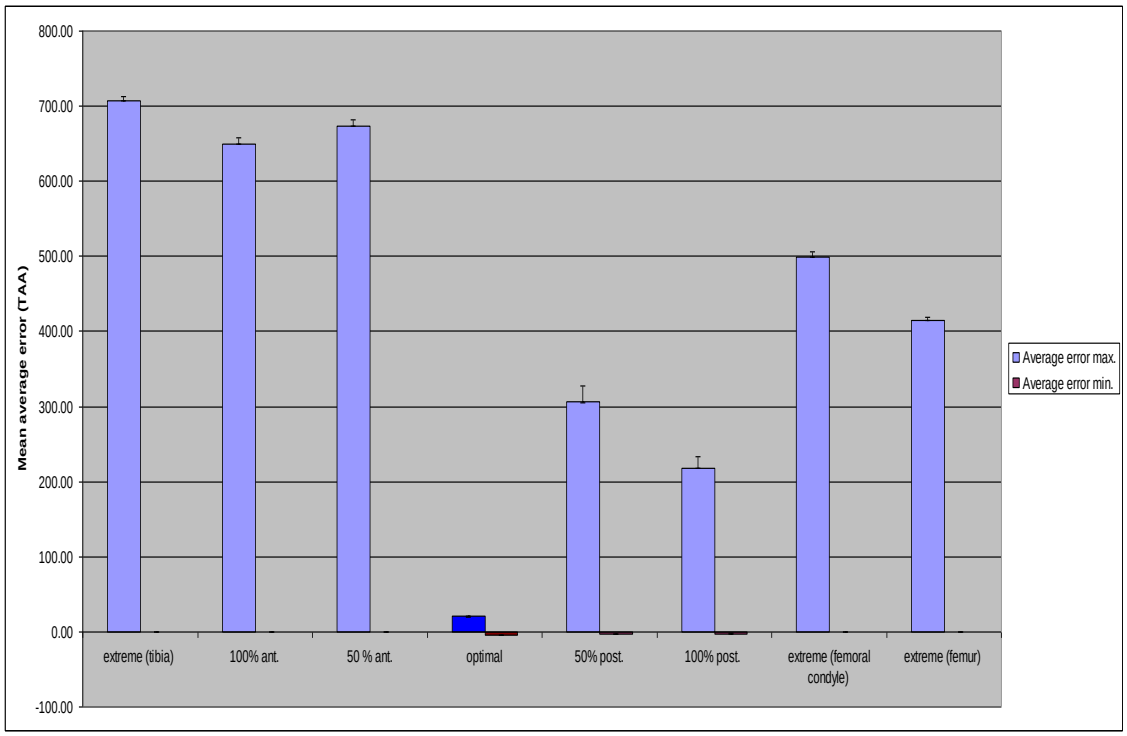


Figure 51. Mean average error maximum and minimum values for the Y axis of the medial line accelerometer at various displacements around the knee joint.

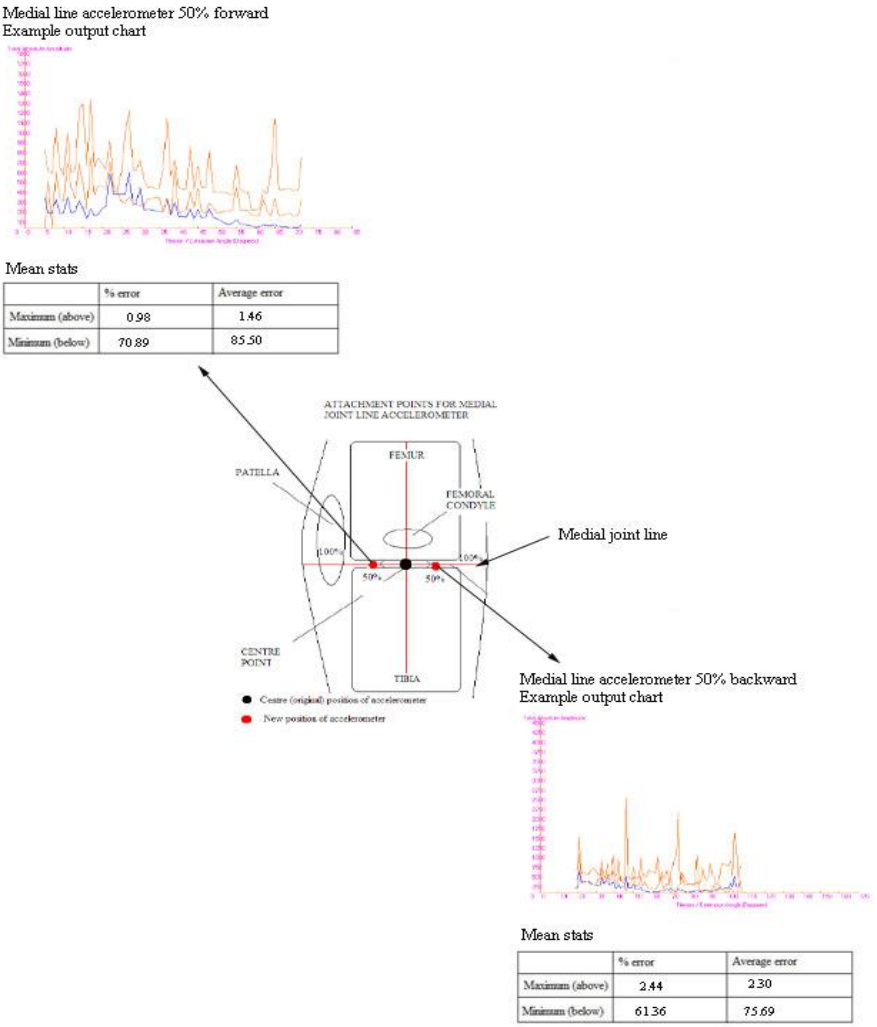


Figure 52. Medial line accelerometer 50% displacement – Z axis

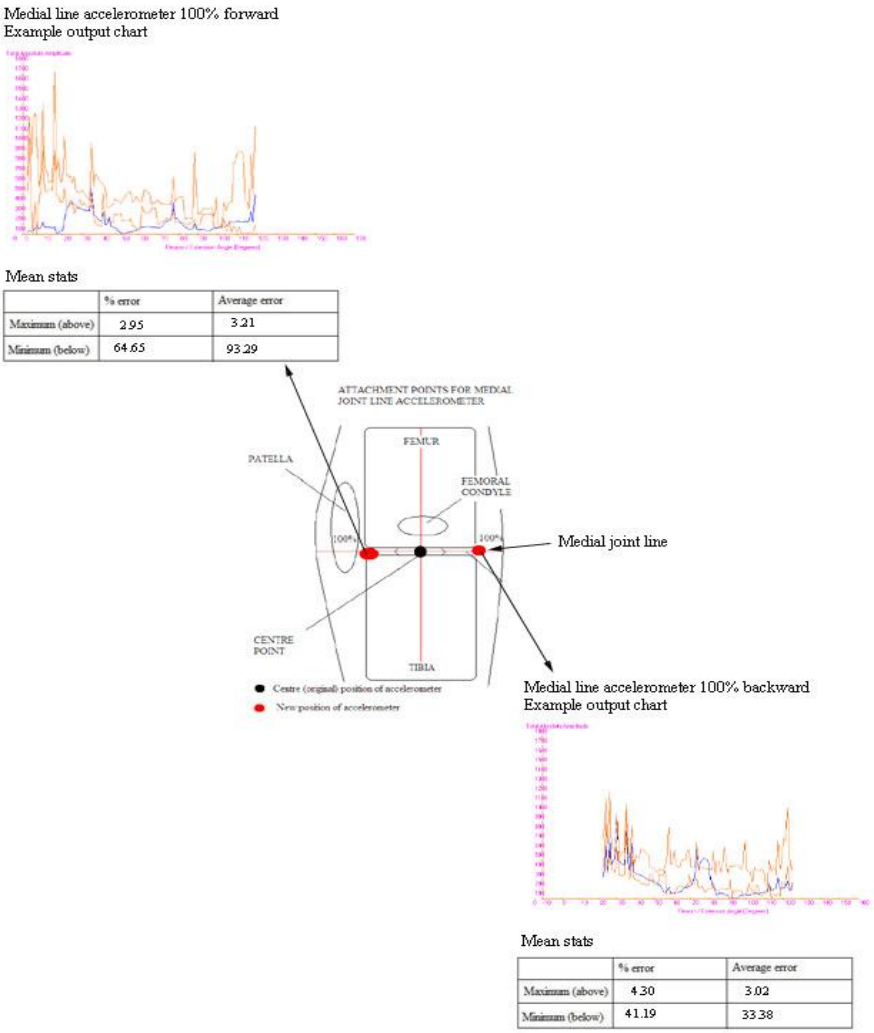


Figure 53. Medial line accelerometer 100% displacement – Z axis

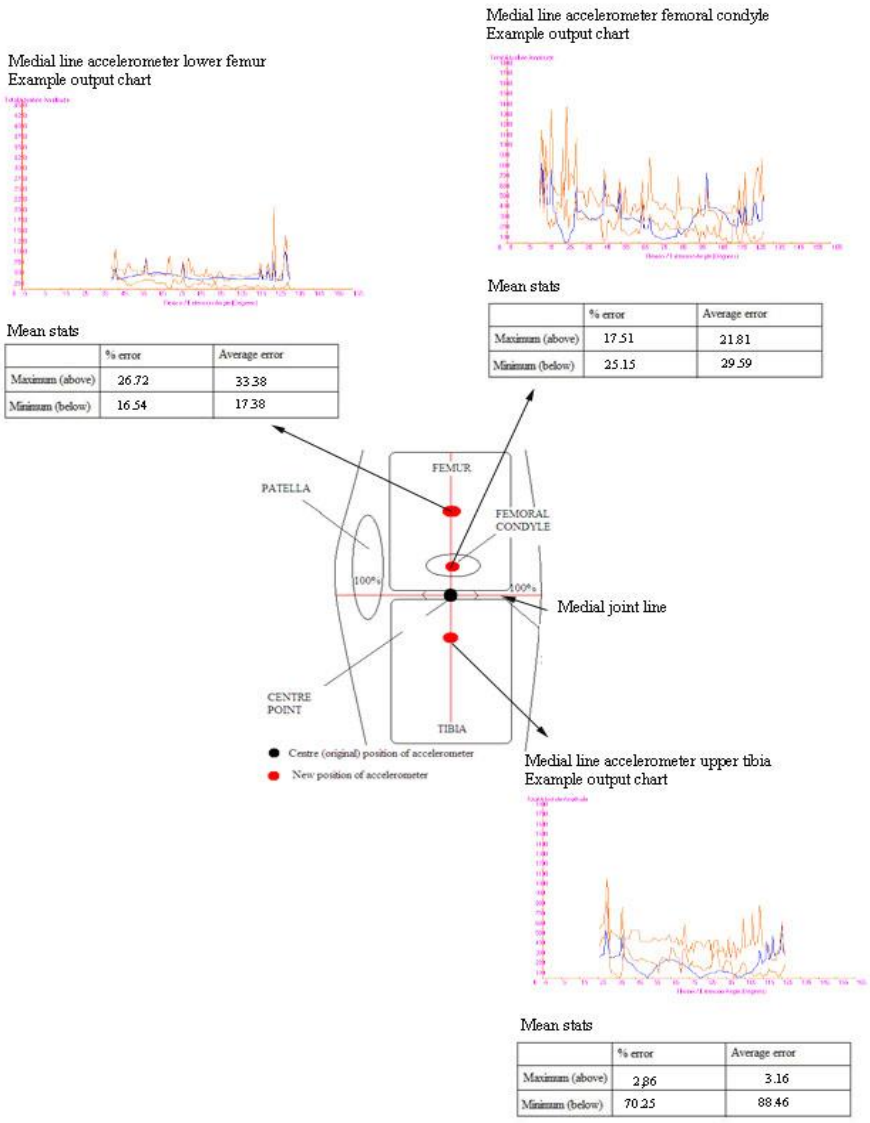


Figure 54. Medial line accelerometer extreme displacement – Z axis.

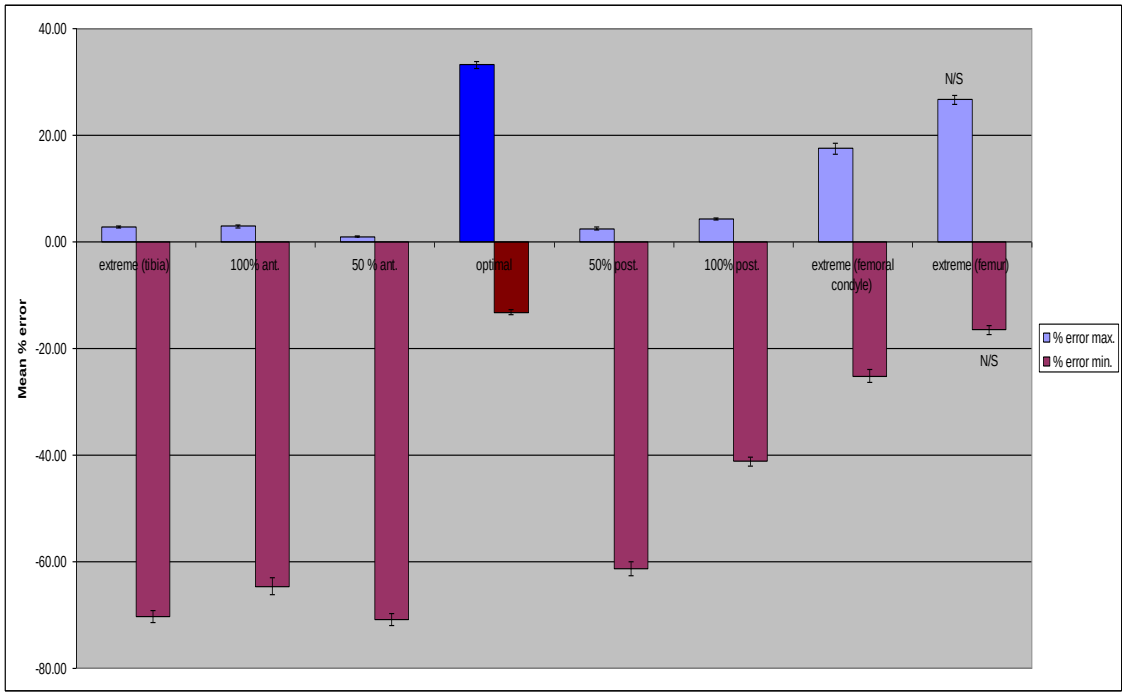


Figure 55. Mean % error maximum and minimum values for the Z axis of the medial line accelerometer at various displacements around the knee joint.

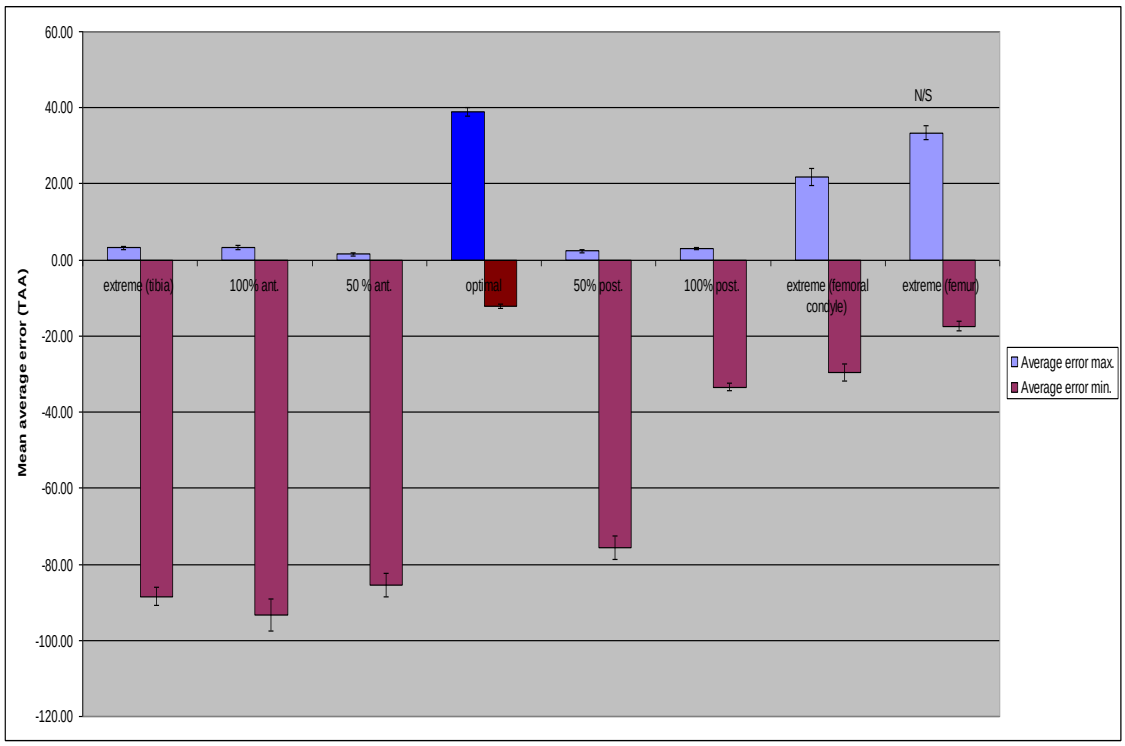


Figure 56. Mean average error maximum and minimum values for the Z axis of the medial line accelerometer at various displacements around the knee joint.

4.53: Discussion

Looking at the preceding results it is clear that placement of the sensor at various places around the knee has a measurable effect on the recorded signal and that a level of variability is introduced to the recorded signal dependant on the placement of the accelerometers. It would seem from this investigation that it is correct to consider that the transmission pathway of the vibration through the knee joint has an effect on the signal detected by the accelerometers and recorded for analysis by the phonoarthrometer software.

The effect that displacement of the accelerometer has is however, not uniform across the accelerometer axes, the greatest effect is observed in the Y axis, displacement by even 50% caused marked increases in the values for % error maximum and average error maximum. The exception to this is the 50% lateral displacement for the patella accelerometer which showed a level of suppression or values which were not significantly different from the optimal. However, where an effect is seen, the values observed are often magnitudes greater than those observed in similar displacements for the X and Z axes. For instance the patella accelerometer shows % error maximum values near the 100% level and average error maximum values in the 420- 716 TAA range.

The effects are next most noticeable in the Z axis, these however are notable in that the signal is mainly suppressed when the accelerometer is moved, values for % and average error minimum increase. In effect displacement of the accelerometers causes the opposite effect to that observed in the Y axis. However, individual values do not reach the level seen in the Y axis, for instance % error minimum values are in the 64-83% range and average error minimum values range from 13-142 TAA.

The X axis displays the most stability with regards to placement of the accelerometer. Variation in the recorded signal is slight at the 50% range and only shows a slight tendency towards increase when displaced to greater distances. It should be noted however, that majority of the results are still significantly different from that of the optimal placement, suggesting that even a 50% displacement of the accelerometer has potential to introduce error into the resultant data.

Given that this level of introduced error occurs in many instances within even the 50% displacement range, it could be suggested that errors may occur at much lower displacement level, for instance at levels as low as 25% in the X axis and possibly as low as 10% in a highly sensitive axis such as seen in the Y axis. If a linear relationship is assumed between the optimal and 50% range then even 25% misplacement will result in errors of approximately 40% error maximum and 300 average error maximum for the patella Y axis. Such errors were not seen in the final dataset used as they would have negated the strong suppression effect seen in the data (see chapter 5: Results). It could be theorised that the relationship between optimal placement values and 50% misplacement values is not linear and that it is either strongly exponential at some point between optimal and 50% or the there is a distinct threshold point at which these errors become apparent. In order to fully test this effect further research would be needed placing the sensors at a gradated range of values between optimal and 50% displacement. One further consideration is that such an experiment may be limited by the size of the accelerometer itself as smaller displacements would require an overlap of the placement area of the accelerometer.

The fact that differences are seen dependant on the axes tested suggests that collection of the signal is influenced in part by the particular plane in which it is being collected. It could be suggested that collection in the horizontal plane (Y axis) is very sensitive to changes in the placement location and the signal directly coming out of the knee (Z axis) is next most sensitive with finally the vertical plane (X axis) showing the most stability.

The implications from these results are therefore of great significance to future research that involves the placement of accelerometers at defined points on the knee joint (or for that matter on any joint being tested). The results presented here suggest strongly that incorrect placement of the sensors at points on the knee joint other than those carefully defined will lead to a change in the nature of the vibration response recorded, and that this in turn could result in the incorrect identification of a normal healthy knee joint as an abnormal one.

This experiment also suggests that careful observation of the Y and Z axes should allow distinct patterns within results to be identified which would lead to the detection of misplaced accelerometers. In a normal knee joint being tested with incorrectly placed

accelerometers this will manifest as a clear shift of the recorded vibration response in the Y axis above the prediction corridor and below the prediction in the Z axis. In an osteoarthritic knee this shift could possibly result in the Y axis appearing normal however the Z axis would produce the opposite with a characteristic shift below the prediction corridor seen in the main osteoarthritic results (see following chapter).

The results presented here highlight the importance of the accurate placement of the accelerometer sensors in the correct position, a point that has not previously been identified and seems to have been overlooked in previous research with regards to the use of these sensors in attempting to analyse the vibration signal response from the knee joint.

It must also be considered from this experiment that the positions denoted for use are not necessarily the best locations on the knee for attachment of the accelerometers. For the purposes of this study they were chosen to be palpable and congruent with the development of the phonoarthrometer which in turn was lead by the existing literature at the time of development. Such locations as are suggested in the literature seem to have been chosen due to the human preference for symmetry and order with central points and easily identified anatomy as the chief concern rather than the quality of the signal that is collected. Whilst these are good initial starting points, this research raises the possibility that these may not be the best locations on the knee joint to obtain the best quality vibration signal.

The results presented here could suggest that other positions may be more preferable for better recording of the vibration signal. It could be suggested that a location at the edge of the patella either above or below the centre point for the patella accelerometer and forward of the medial centre point for the medial line accelerometer may result in a better placement for the collection of the vibration signal due to the enhanced signals observed in this experiment. This is a tentative recommendation and will require this experiment to be expanded considerably and tested this more fully before anatomical locations on the knee joint can be defined that will maximise the vibration response collected. It is clear from this experiment that before any future development of the phonoarthrometer it would be wise to devote more research time to the investigation of the optimal placement of the accelerometers.

Finally it can be said that these results underline the importance of correct placement of the sensors for all the subsequent results as presented in the following sections. Great care was taken in the placement of the sensors at the correct locations, this being achieved through the reliable identification of the specifically defined anatomical landmarks prior to placement of the sensors. The collected data was also carefully screened post processing for the particular levels of error associated with misplacement, specifically by observation of the Y axis for high levels of deviation. Analysis of the resultant data shows that placement of the sensors was acceptably accurate, as no such obvious pattern of abnormality in the Y axis or suppression in the Z axis was identified in the data collected for either the normal or the osteoarthritis affected data sets. However, a possible exception is OA16 who on analysis by the phonoarthrometer software could be considered as exhibiting results that tend towards the patterns observed here. This pattern is by no means conclusive and only a suspicion can be implied due to high error maximum values for the Y axis being observed. The participant had a high BMI, and excessive body mass around the joint obscured the selected anatomical landmarks to a large extent, this could account for some degree of sensor misplacement. As a precaution OA16 was removed from the final osteoarthritic dataset. The loss of the data recordings from one individual was deemed to be a preferable sacrifice compared to inclusion that may have masked any observation of detection ability found in the final dataset. No cause was found to remove any further data due to sensor misplacement error, suggesting that the issue was successfully managed by accurate identification of the anatomical landmarks and subsequent careful placement of the accelerometers.

4.6: Summary.

In summary this chapter has shown an overview of the practicalities involved in using the phonoarthrometer. It has also described the nature and appearance of the raw data collected and what if anything can be extracted from it.
The process of constructing the microstructure library, integral in the operation of the phonoarthrometer, has been described in some detail.
Finally it concludes with the results of the preliminary experiment, being concerned with the limitations of the phonoarthrometer in terms of the accurate placement of the accelerometers on the knee joint and that accurate placement is vital for consistency in the data collection and that a distinct pattern relating to the accelerometers individual axes can be observed when the sensor placement is transposed to locations differing from those originally defined.

Chapter 5

Results

5.1: Introduction.

This chapter focuses on the resultant data attained after the software processing phase. This processed data was taken from 74 individual participants with a total of 10,514 individual flexion/extension sequences from the knee joints tested. All subsequent analysis for this study uses this as a final data set.

The following chapter is split into three distinct groupings. The first section is a concerned with any difference between the osteoarthritic and the normal group data, in order to test the hypothesis that a knee joint affected by osteoarthritis will produce a different response to a normal uninjured knee joint.

Secondly a number of knee joints with medial or lateral compartment osteoarthritis are identified, these are compared once again with the normal group in order to test the hypothesis that specific areas of osteoarthritis are identifiable due to the nature of the transmission pathway of the vibration signal through the knee joint and whether the use of two accelerometers allows a level of triangulation of the signal to be possible.

Finally the osteoarthritic group data is divided according to level of severity of the osteoarthritic lesion within the knee (as recorded in the surgeon's notes and using the Kellegren-Lawrence scale), this is then compared once again with the normal group and between each grade of severity in order to determine whether a degree of gradation is observable in the data.

5.2: Comparison of the osteoarthritic knee joint data with normal knee joint group data.

The following section presents the data as a series of graphs showing the mean values of % min/max error and average min/max error for the osteoarthritic group and the normal group. The data is divided according to the protocol type performed (swing (unloaded), walking (loaded) and sitting/rising (loaded)) and according to the accelerometer position (patella or medial line) used to collect the vibration signal. Positive values denote % and average error maximum values, negative values denote % and average error minimum values in each case, in effect these represent the level of deviation for each group above (maximum) or below (minimum) the prediction corridor as produced following analysis of the vibration signal by the phonoarthrometer software. For each plotted data point error bars are shown, representing the standard error of the sample means. T test comparisons of the sample means were carried out for each error min/max dataset, with the significance level set at $p<0.05$. Results of the comparisons are denoted by the shown p values, non-significant results are denoted by n/s before the p value. It should also be noted that actual recorded data values for % and average error min are positive; the values were plotted negatively in order to graphically represent % and average error falling below the prediction corridor.

5.21 Swing (unloaded), osteoarthritic versus normal.

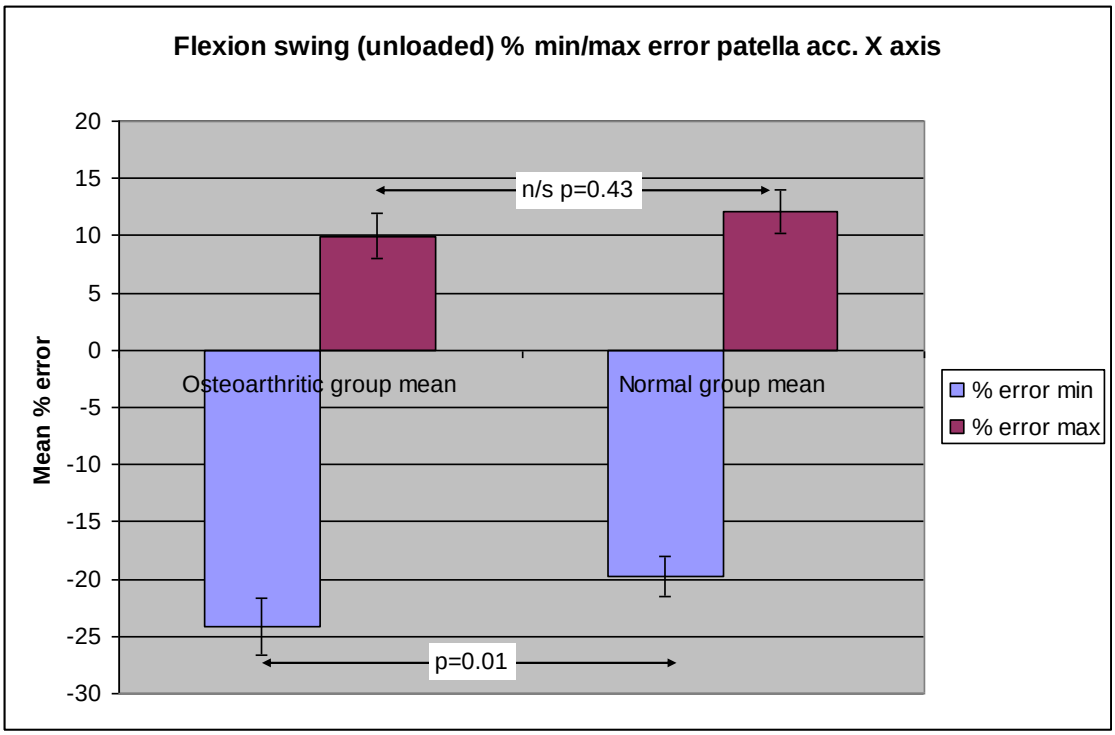


Figure 57. Mean values for swing (unloaded) % min/max error, OA vs. normal group, X axis of the patella accelerometer.

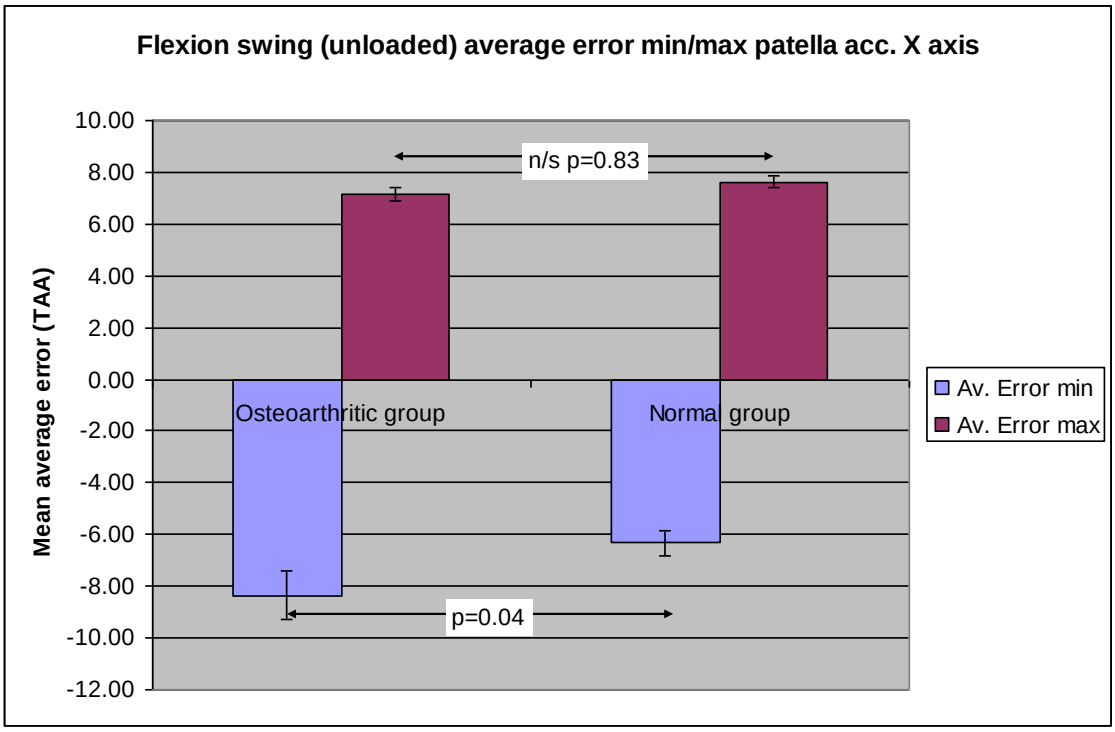


Figure 58. Mean values for swing (unloaded) average min/max error, OA vs. normal group, X axis of the patella accelerometer.

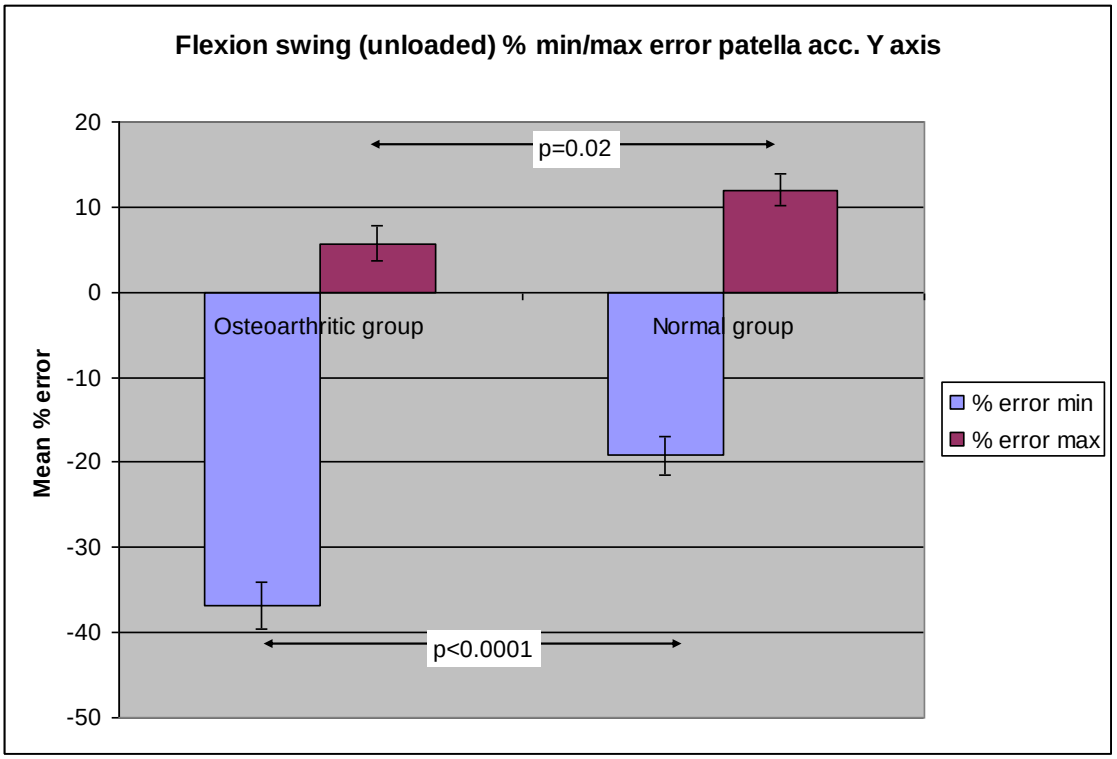


Figure 59. Mean values for swing (unloaded) % min/max error, OA vs. normal group, Y axis of the patella accelerometer.

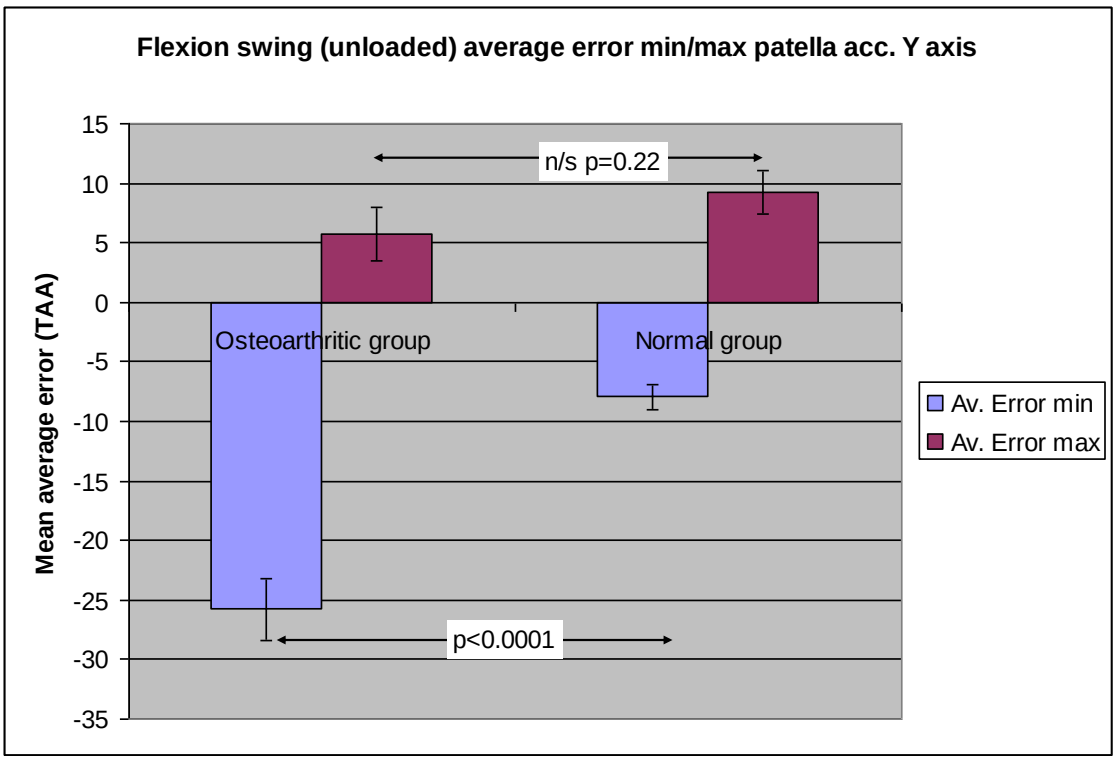


Figure 60. Mean values for swing (unloaded) average min/max error, OA vs. normal group, Y axis of the patella accelerometer.

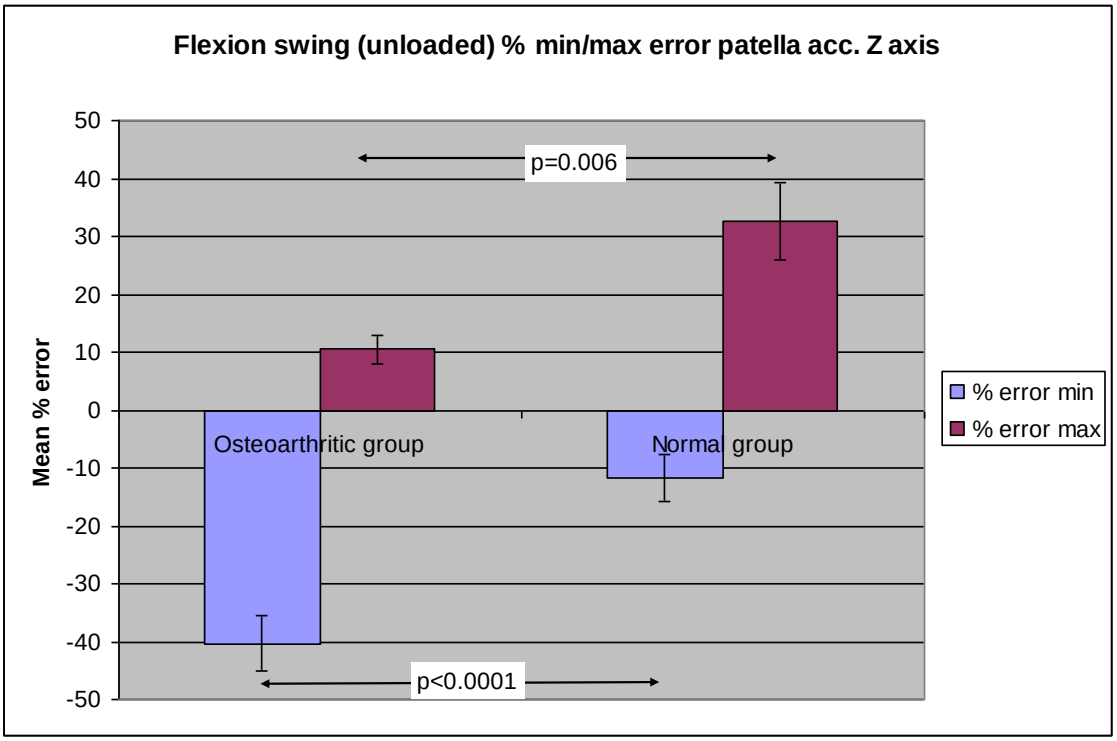


Figure 61. Mean values for swing (unloaded) % min/max error, OA vs. normal group, Z axis of the patella accelerometer.

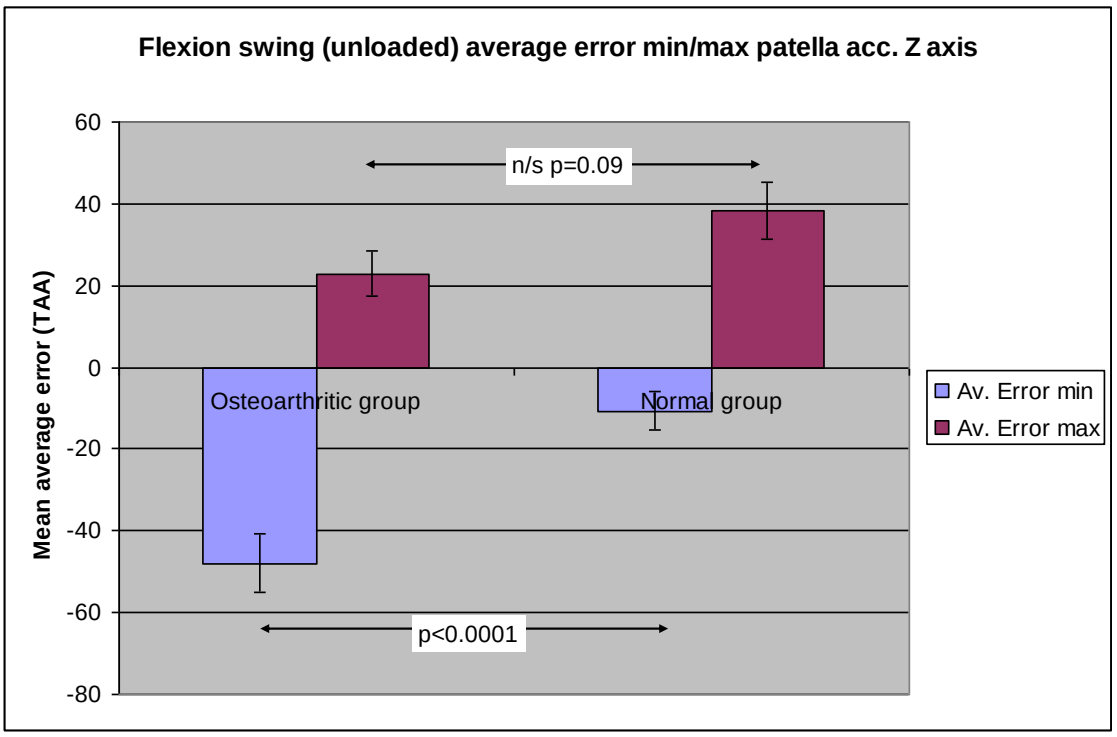


Figure 62. Mean values for swing (unloaded) average min/max error, OA vs. normal group, Z axis of the patella accelerometer.

The preceding figures 57-62 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X Y and Z axis of the patella accelerometer when performing the swing (unloaded) protocol.

There is a significant difference at the $p<0.05$ level shown between the osteoarthritic affected knee group and the normal knee group in all axes of the accelerometer for the % and average error min values and in the % error max values for the Y and Z axes. Greater values for both average error min and % error minimum and corresponding smaller values for average error maximum and % error max are recorded for the osteoarthritic affected group resulting in the observation of a distinct downward shift of values for the osteoarthritic affected group when compared with the normal knee group. In effect this represents a suppression of the recorded vibration signal from the osteoarthritic affected knee group.

It should be noted that the magnitude of the difference between the osteoarthritic affected group and the normal group is not the same across all axes of the accelerometer. In the X axis this difference is relatively small, and whilst the Y axis exhibits a greater difference it is the Z axis that shows the most obvious difference between the osteoarthritic group values and the normal group.

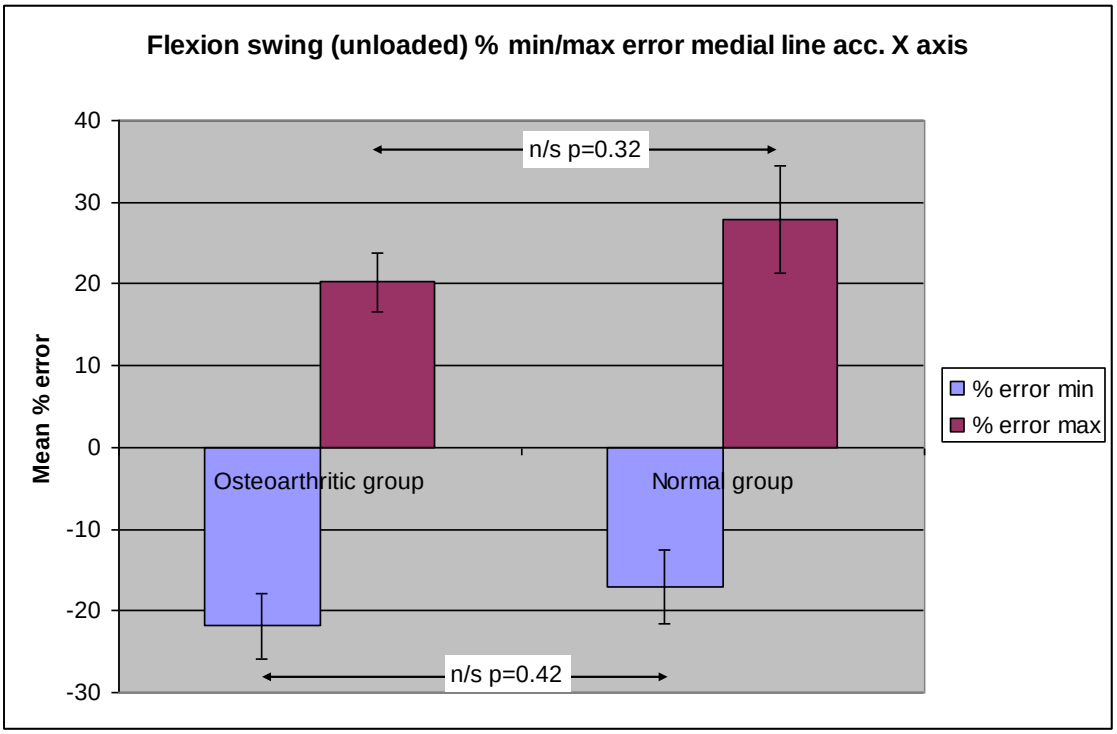


Figure 63. Mean values for swing (unloaded) % min/max error, OA vs. normal group, X axis of the medial line accelerometer.

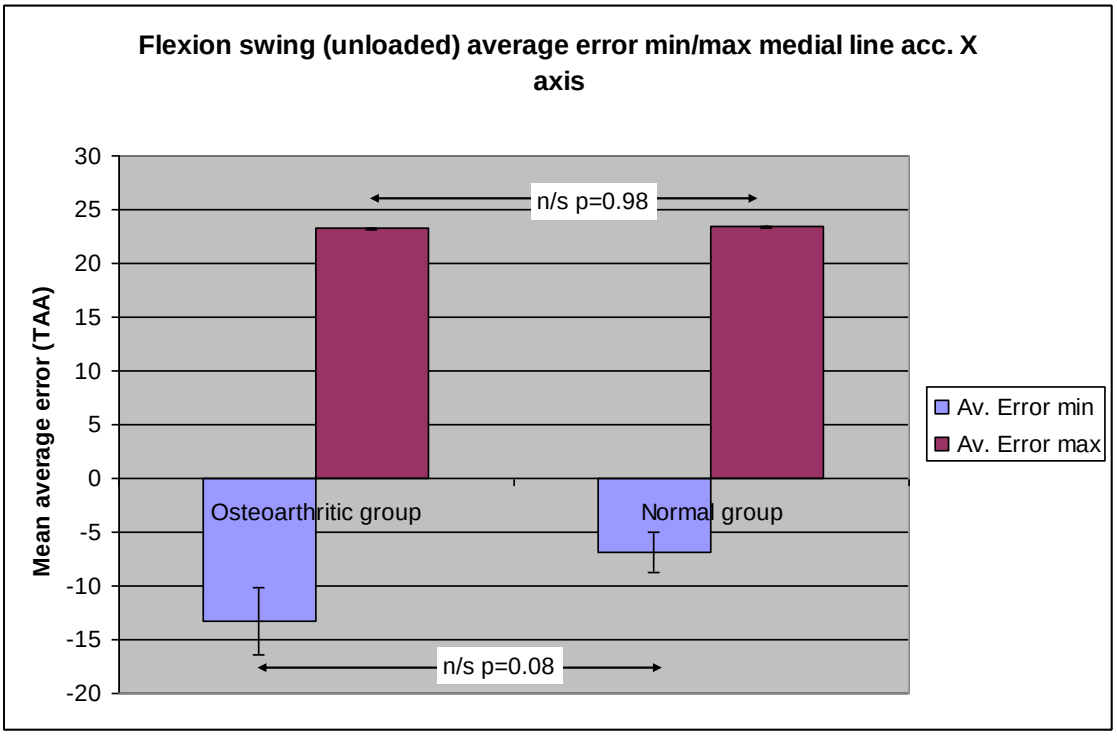


Figure 64. Mean values for swing (unloaded) average min/max error, OA vs. normal group, X axis of the medial line accelerometer.

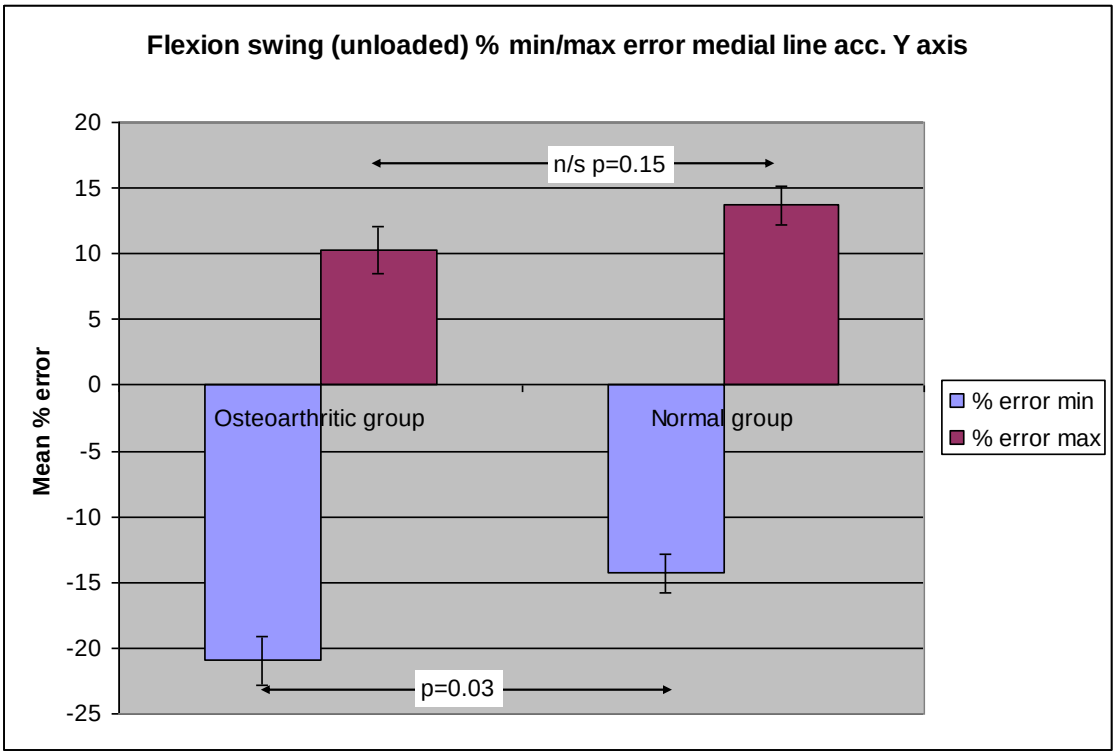


Figure 65. Mean values for swing (unloaded) % min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

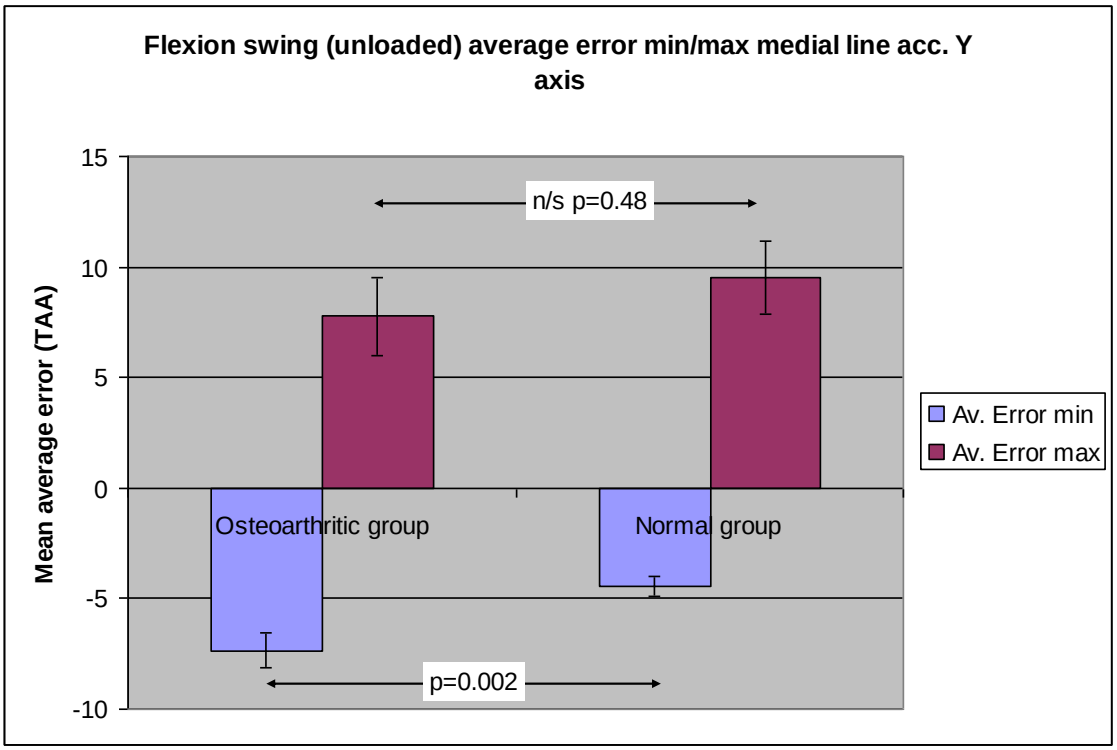


Figure 66. Mean values for swing (unloaded) average min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

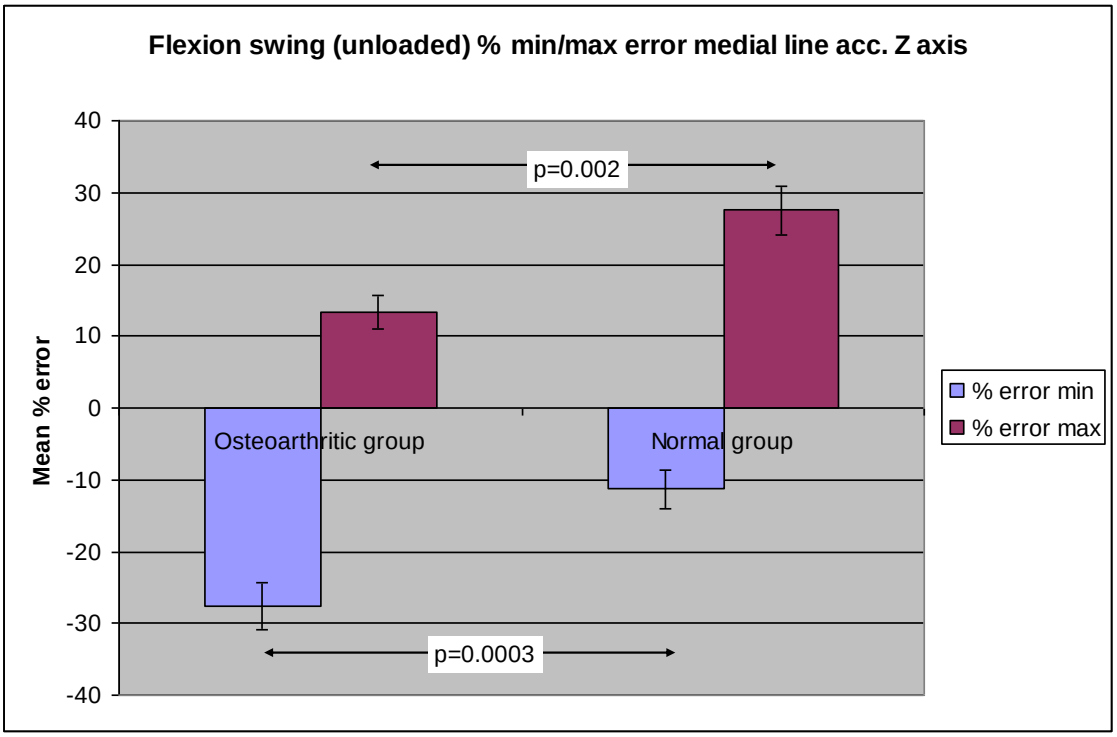


Figure 67. Mean values for swing (unloaded) % min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

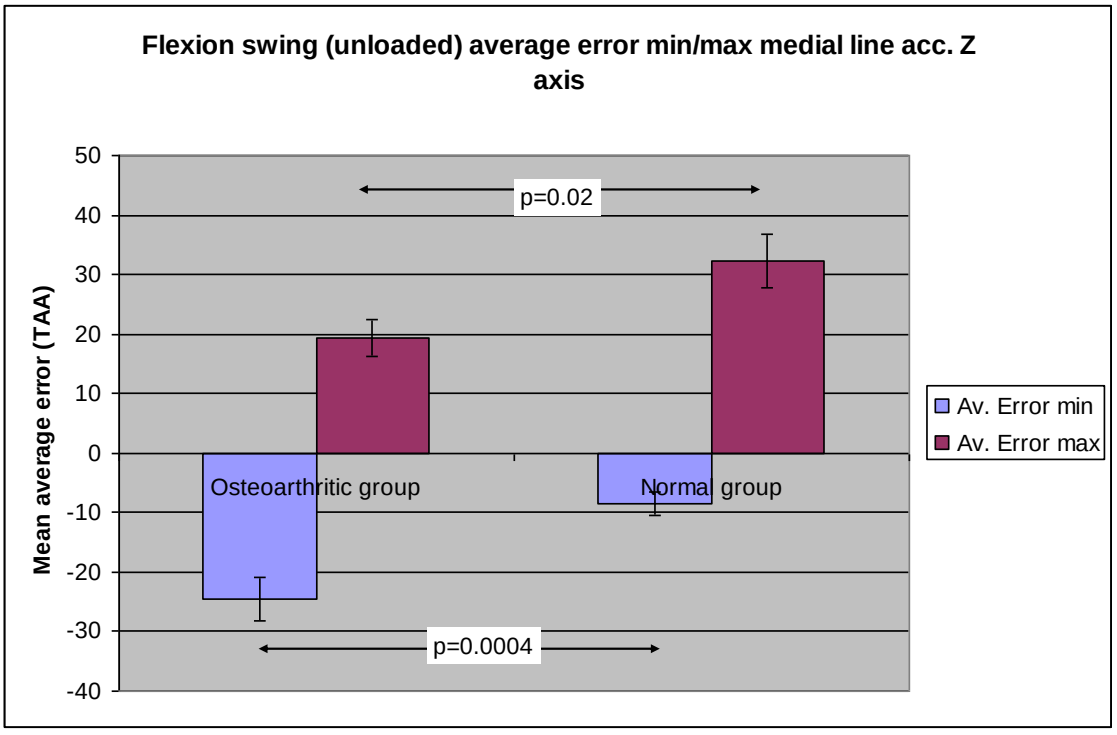


Figure 68. Mean values for swing (unloaded) average min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 63-68 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X Y and Z axes of the medial line accelerometer when performing the swing (unloaded) protocol.

As found in the patella accelerometer there is an observable difference shown between the osteoarthritic affected knee group and the normal knee group however, significant differences in the recorded mean values are only found in the % and average error minimum values for the Y and Z axes and for the %/average error maximum in the Z axis alone. This corresponds to a similar overall downward shift in these axes as observed in the patella accelerometer results.

Broadly described, the values for the medial line accelerometer are similar to those recorded for the patella accelerometer and the magnitude of the difference between the osteoarthritic affected group and the normal group is comparable between the two accelerometers for the Y and Z axes. As noted before the Z axis shows greatest difference, followed by the Y axis, with no significant difference between the osteoarthritic affected group and the normal group means being found in the X axis.

5.22: Walking (loaded), osteoarthritic versus normal.

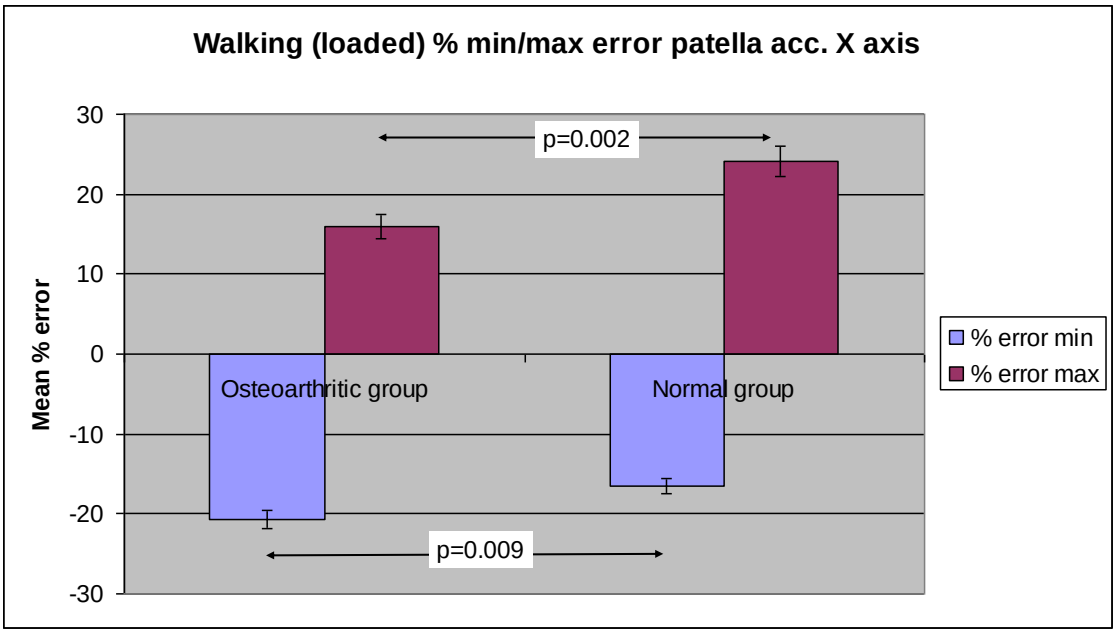


Figure 69. Mean values for walking (loaded) % min/max error, OA vs. normal group, X axis of the patella accelerometer.

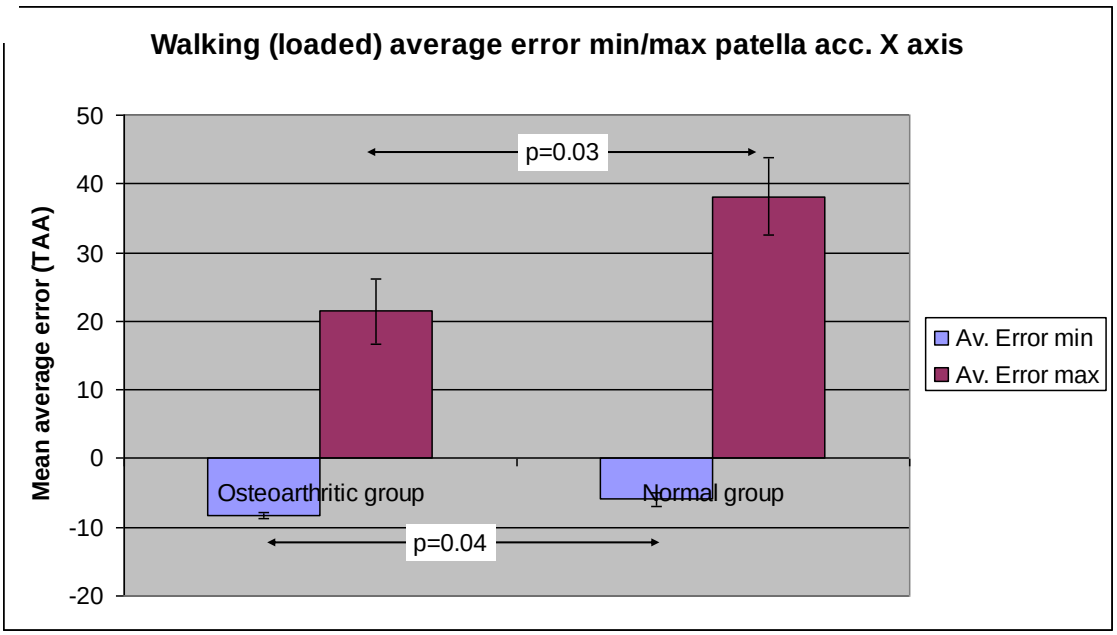


Figure 70. Mean values for walking (loaded) average min/max error, OA vs. normal group, X axis of the patella accelerometer.

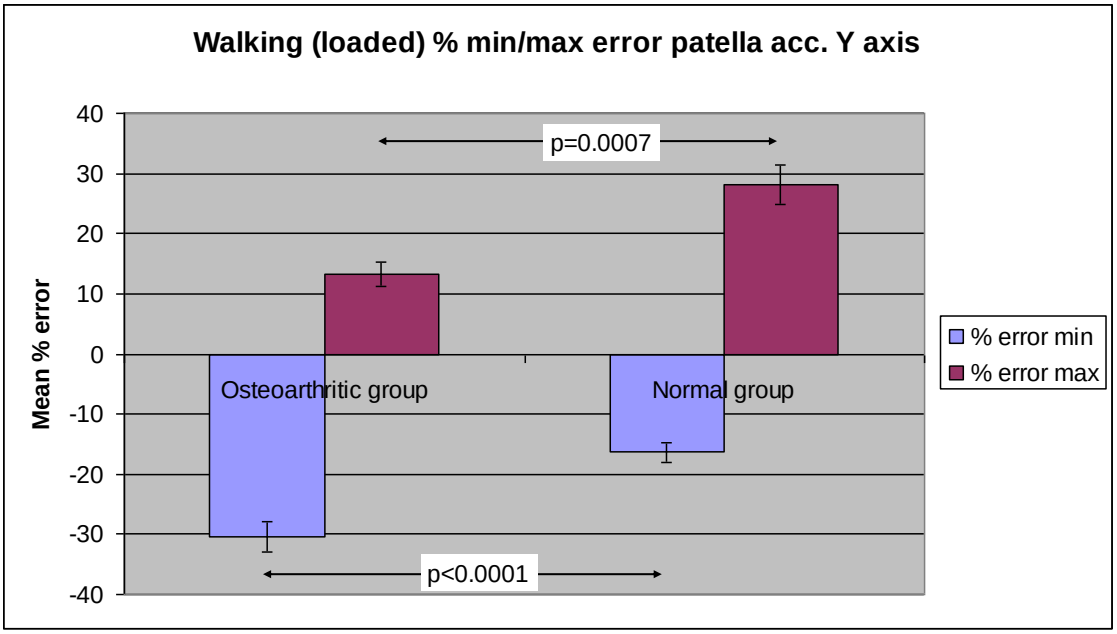


Figure 71. Mean values for walking (loaded) % min/max error, OA vs. normal group, Y axis of the patella accelerometer.

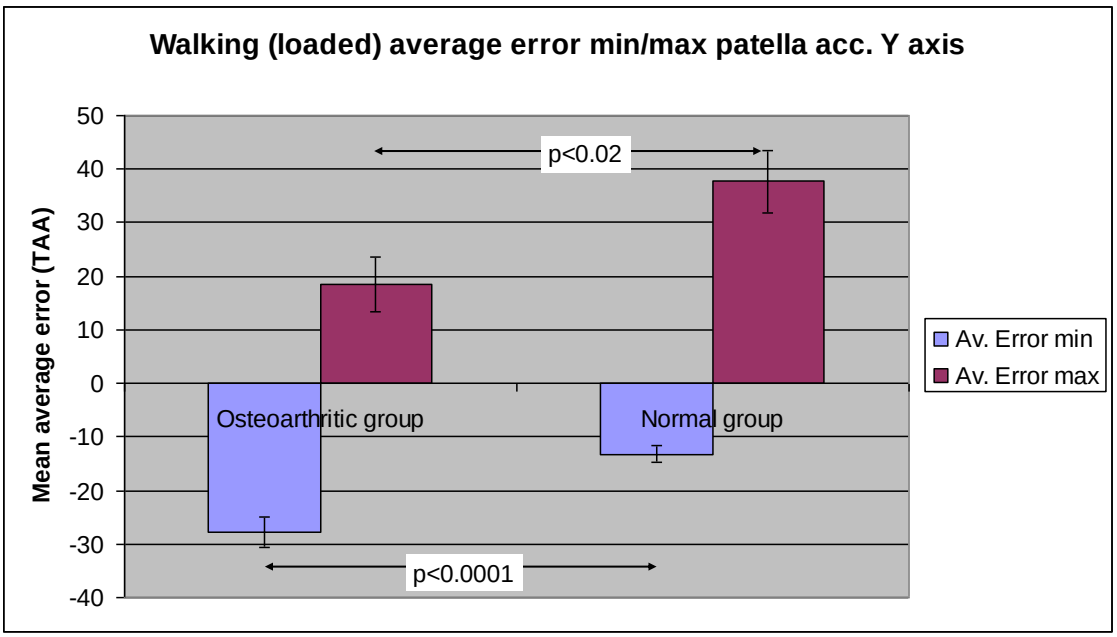


Figure 72. Mean values for walking (loaded) average min/max error, OA vs. normal group, Y axis of the patella accelerometer.

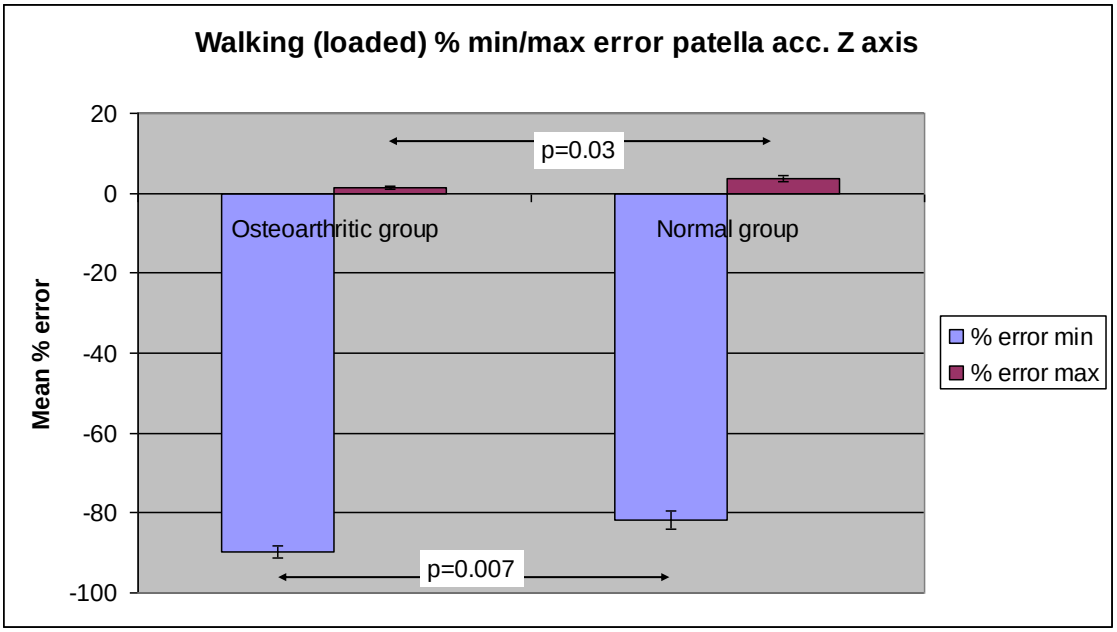


Figure 73. Mean values for walking (loaded) % min/max error, OA vs. normal group, Z axis of the patella accelerometer.

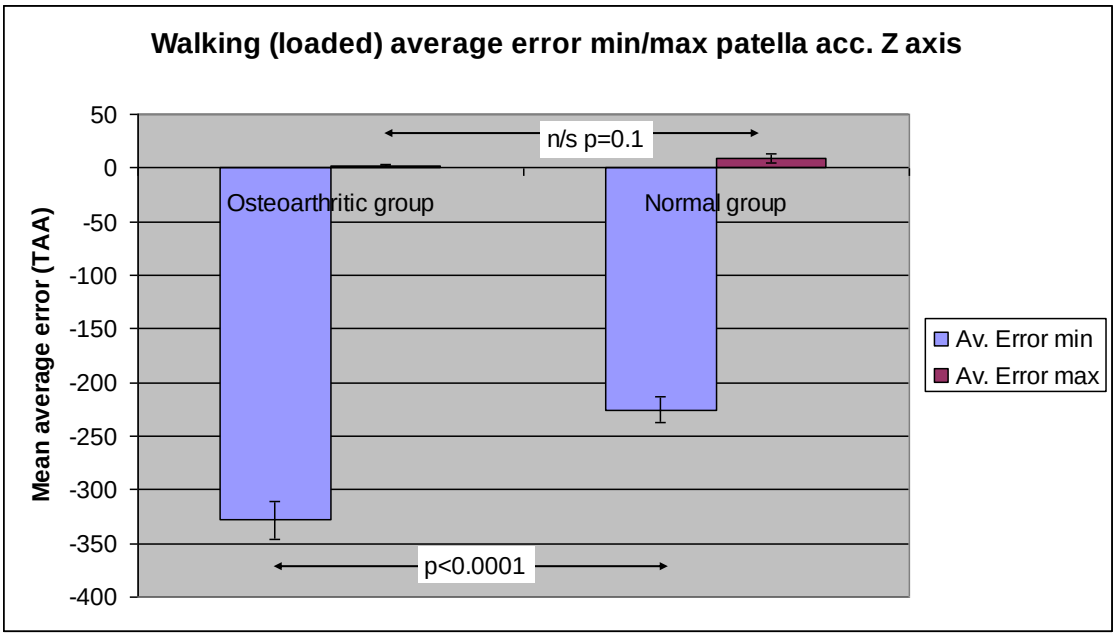


Figure 74. Mean values for walking (loaded) average min/max error, OA vs. normal group, Z axis of the patella accelerometer.

The preceding figures 69-74 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X Y and Z axes of the patella accelerometer when performing the walking (loaded) protocol.

There is a significant difference at the $p<0.05$ level between the osteoarthritic affected knee group and the normal knee group in all axes of the accelerometer. Significantly greater values for both average error min and % error min are found in all axis and corresponding smaller values for average error max and % error max in the X and Y axes are recorded for the osteoarthritic affected group resulting in the observation of a distinct downward shift of values for the osteoarthritic affected group when compared with the normal knee group. In effect this represents a suppression of the recorded vibration signal from the osteoarthritic affected knee group.

In contrast to the X and Y axes readings for the swing (unloaded) protocol this effect is most observable in the % error maximum and average error maximum for the X and Y axes of the walking (loaded) protocol.

The Z axis readings for the walking protocol show higher values for the % error minimum and average error minimum similar in pattern to those found in the swing (unloaded) protocol although they are of considerably higher actual values.

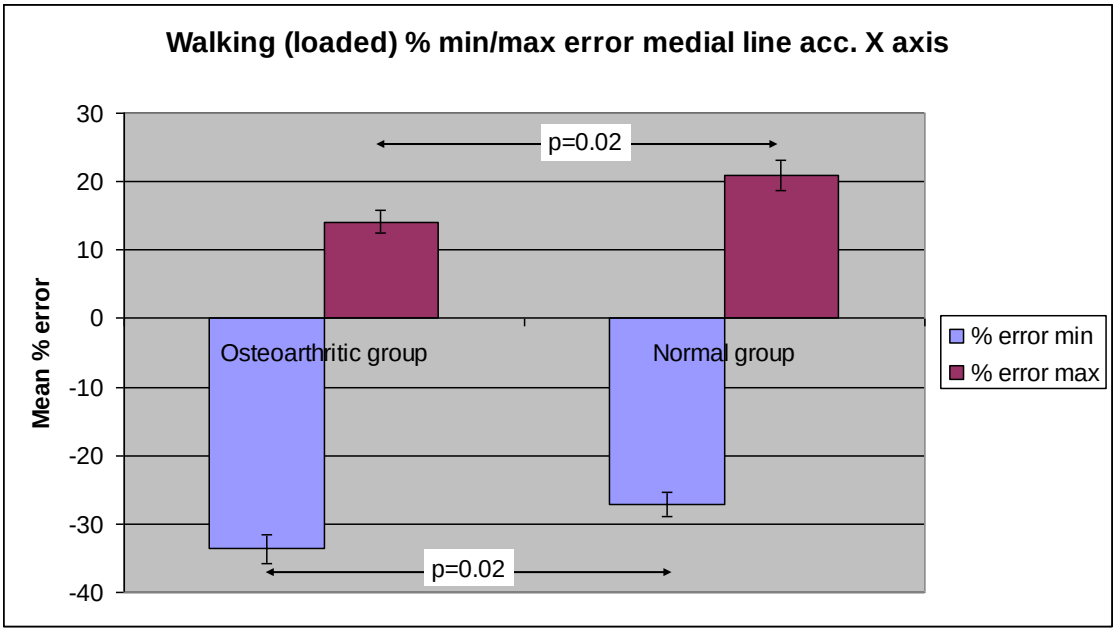


Figure 75. Mean values for walking (loaded) % min/max error, OA vs. normal group, X axis of the medial line accelerometer.

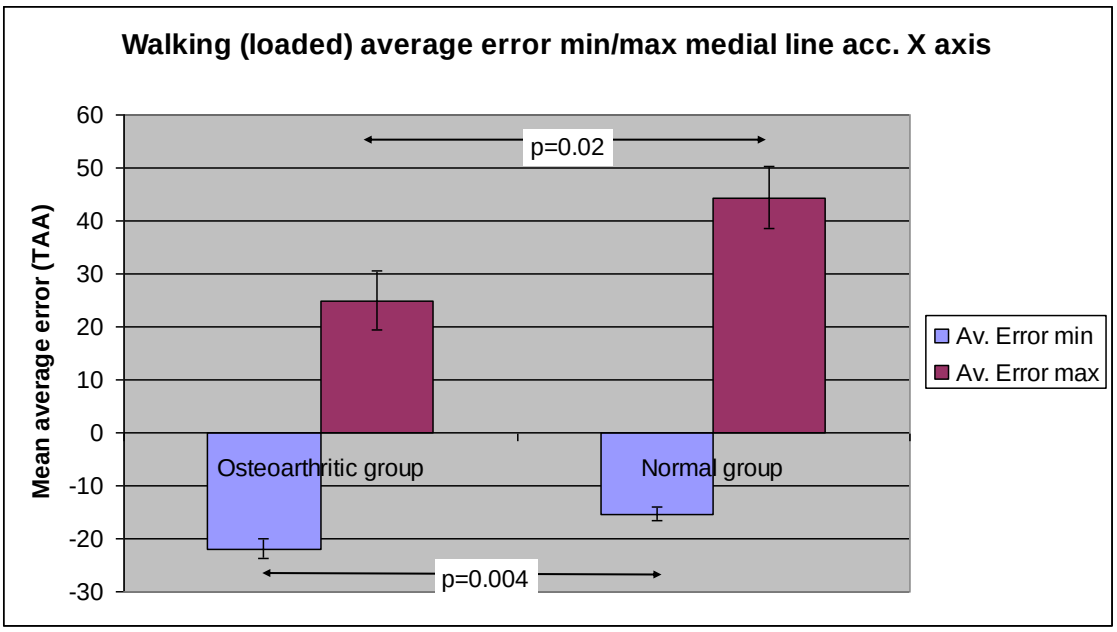


Figure 76. Mean values for walking (loaded) average min/max error, OA vs. normal group, X axis of the medial line accelerometer.

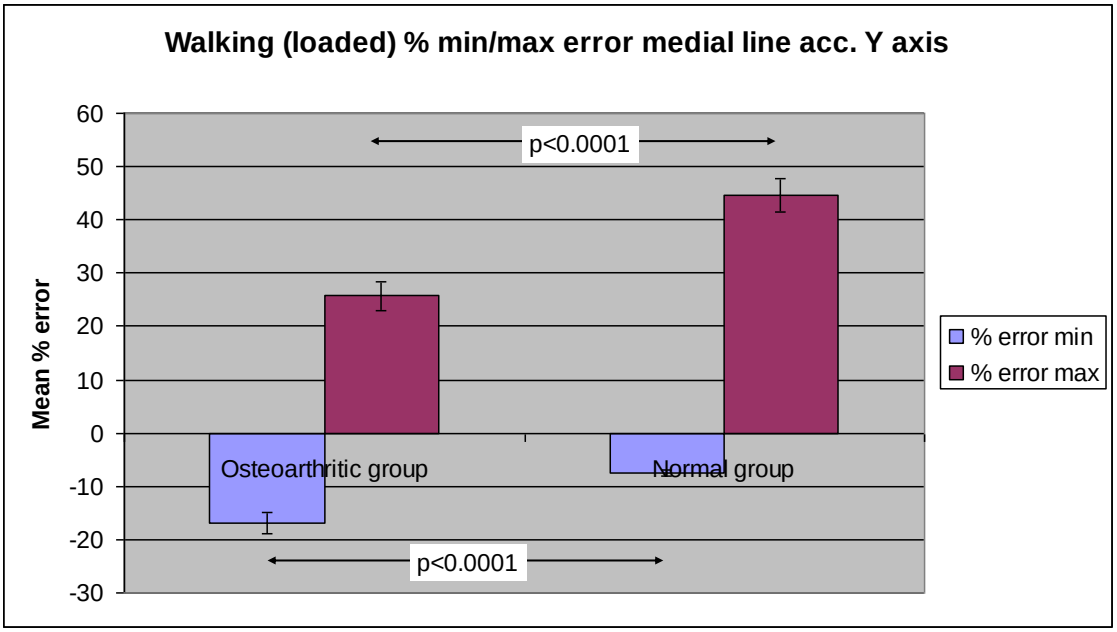


Figure 77. Mean values for walking (loaded) % min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

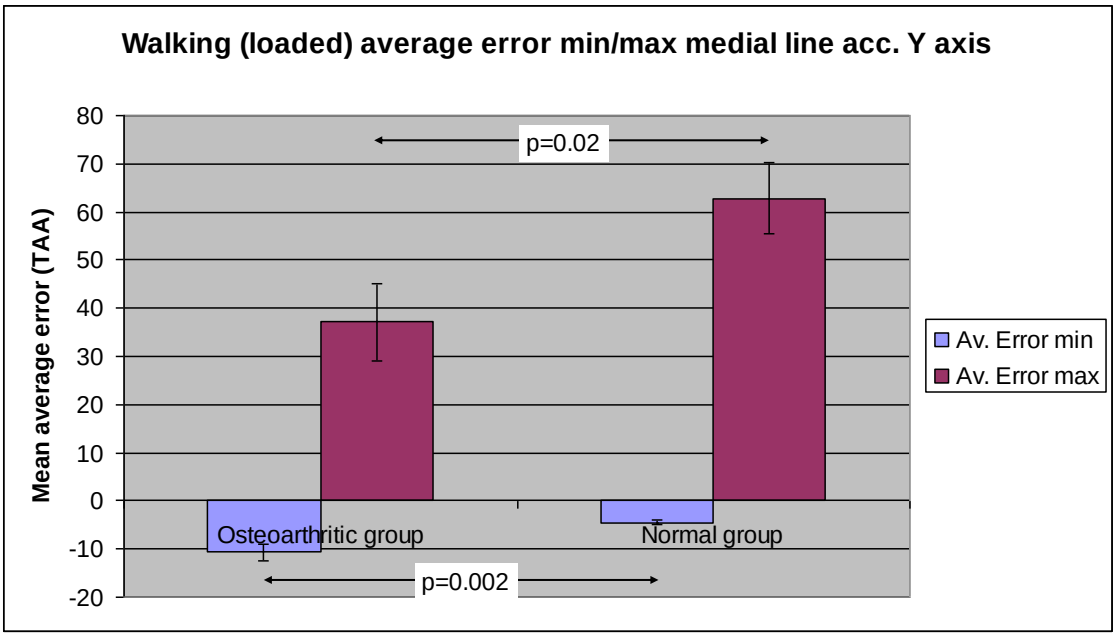


Figure 78. Mean values for walking (loaded) average min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

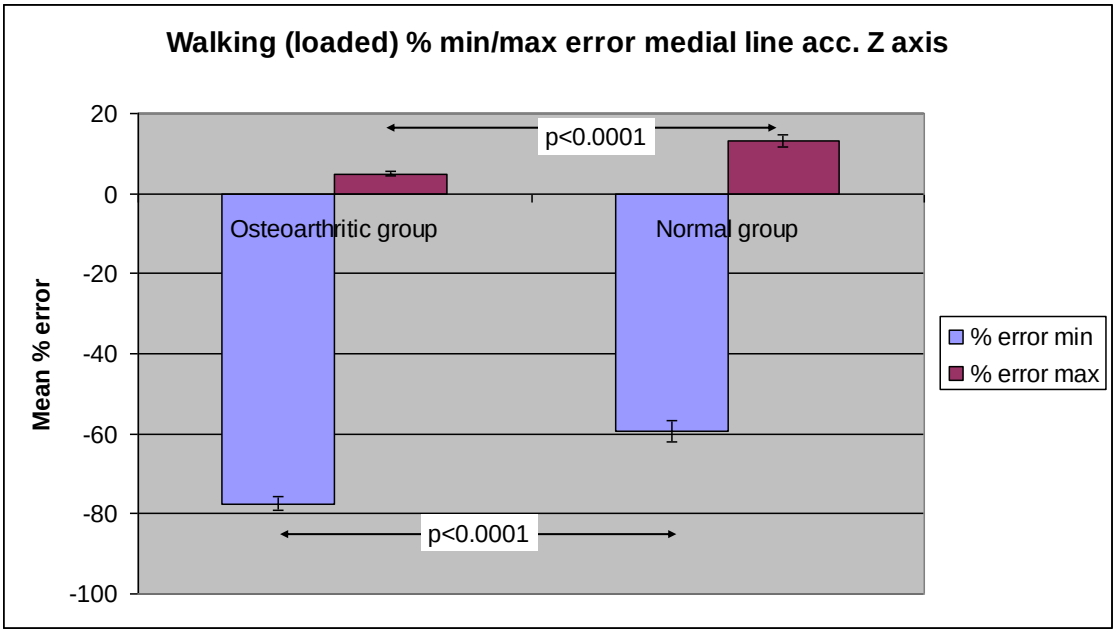


Figure 79. Mean values for walking (loaded) % min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

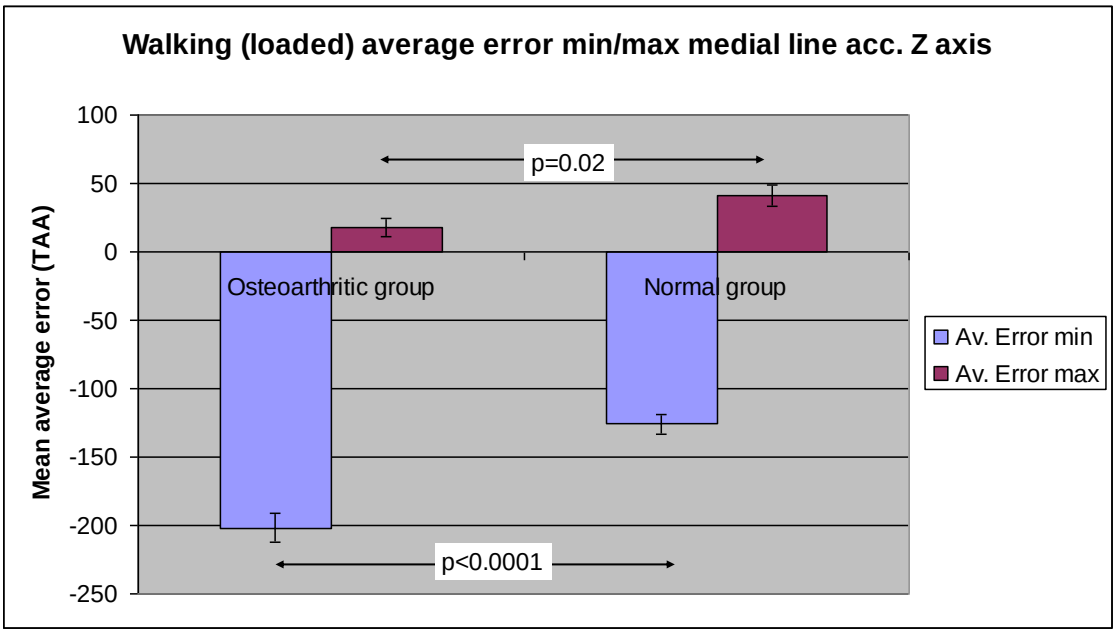


Figure 80. Mean values for walking (loaded) average min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 75-80 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the walking (loaded) protocol.

Once again significantly greater values for both average error min and % error min and corresponding smaller values for average error max and % error max are recorded for the osteoarthritic affected group than for the normal group; however this effect is seen in all axes for both minimum and maximum values. A distinct downward shift of values for the osteoarthritic affected group when compared with the normal knee group is once again seen

A similar pattern as described for the patella accelerometer X and Y axes readings is also seen, with higher values for % error maximum and average error maximum than those found in the swing (unloaded) protocol.

Similarly the Z axis readings for the medial line accelerometer show higher values for the % error minimum and average error minimum and these reading are of a higher magnitude than those recorded for the swing (unloaded) protocol.

5.23: Sitting/rising (loaded), osteoarthritic versus normal.

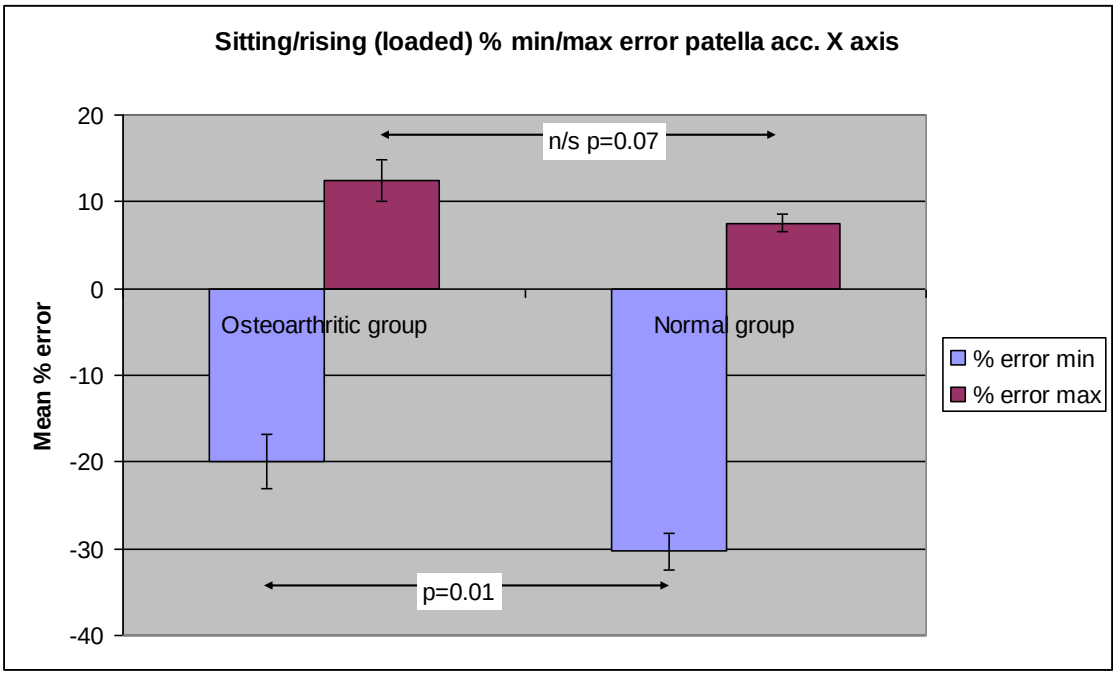


Figure 81. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, X axis of the patella accelerometer.

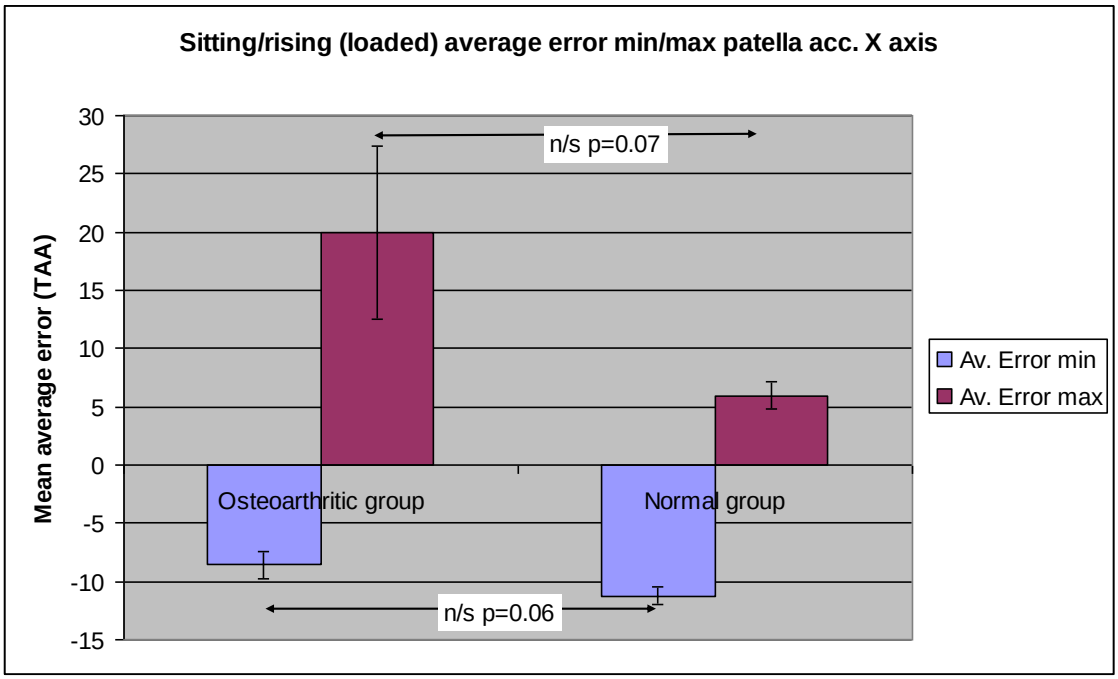


Figure 82. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, X axis of the patella accelerometer.

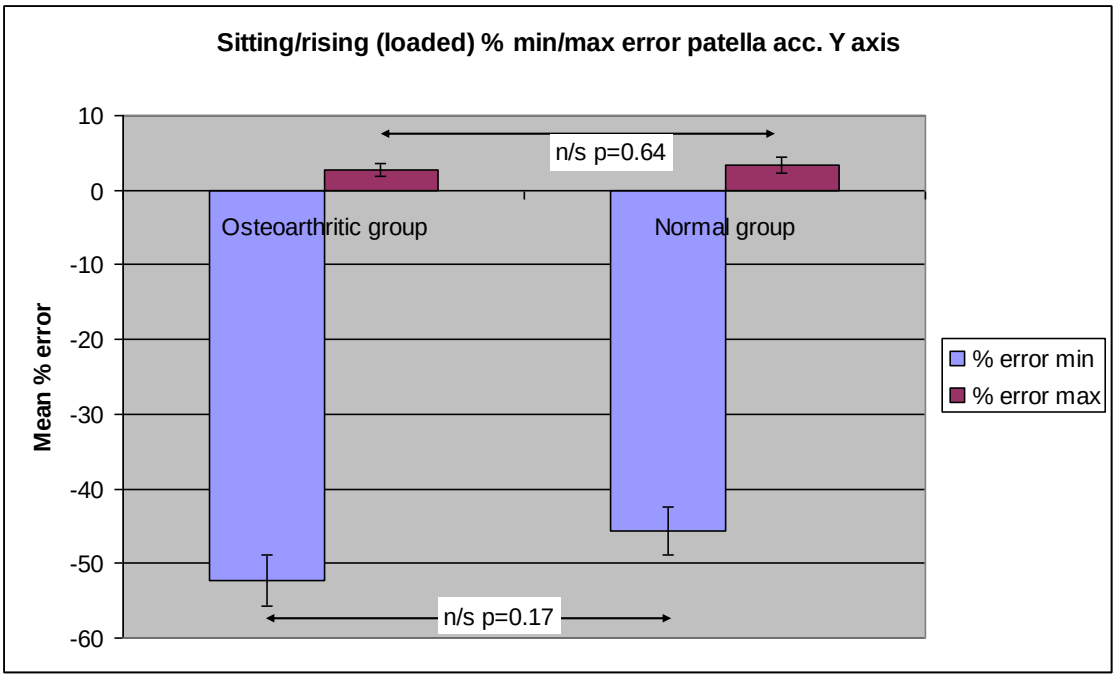


Figure 83. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, Y axis of the patella accelerometer.

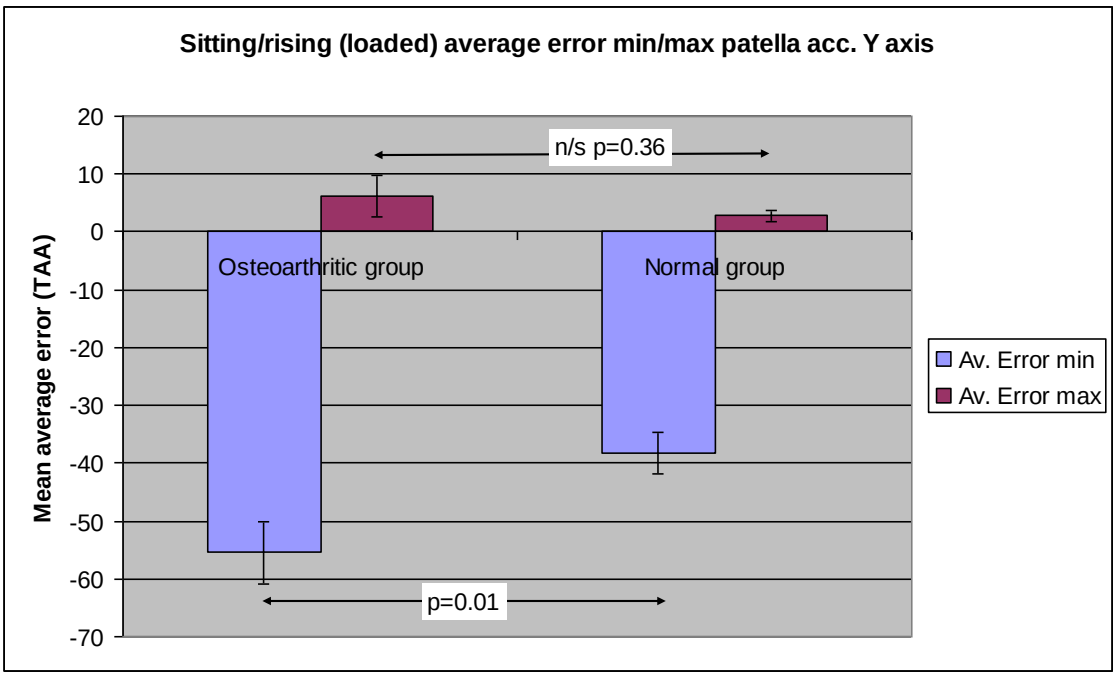


Figure 84. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, Y axis of the patella accelerometer.

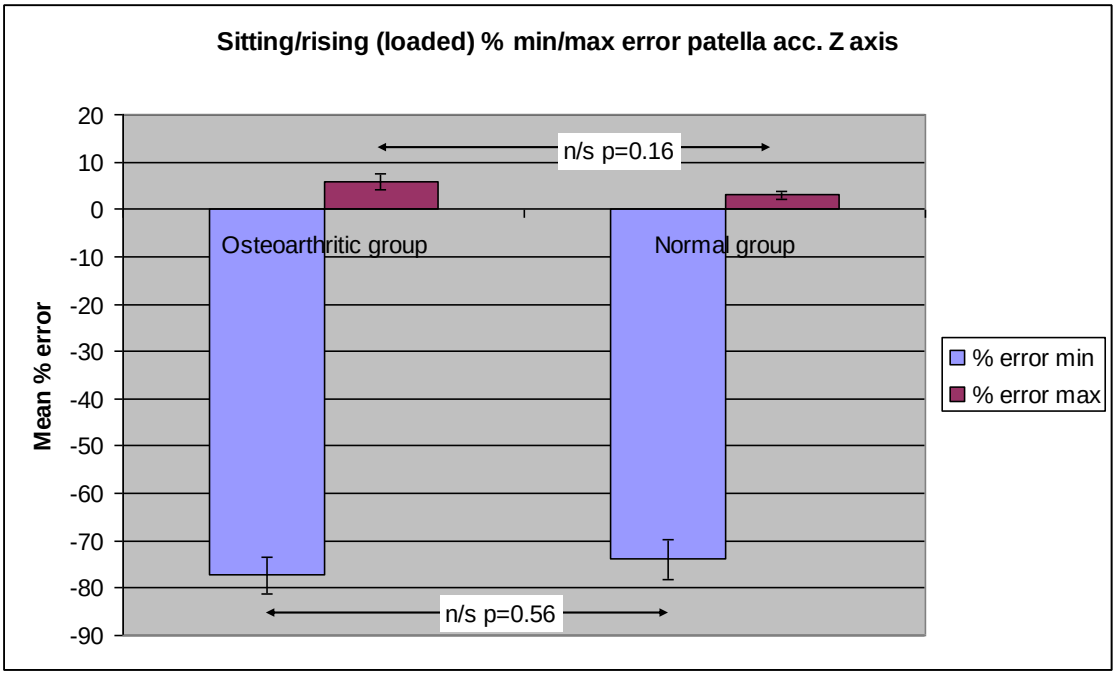


Figure 85. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, Z axis of the patella accelerometer.

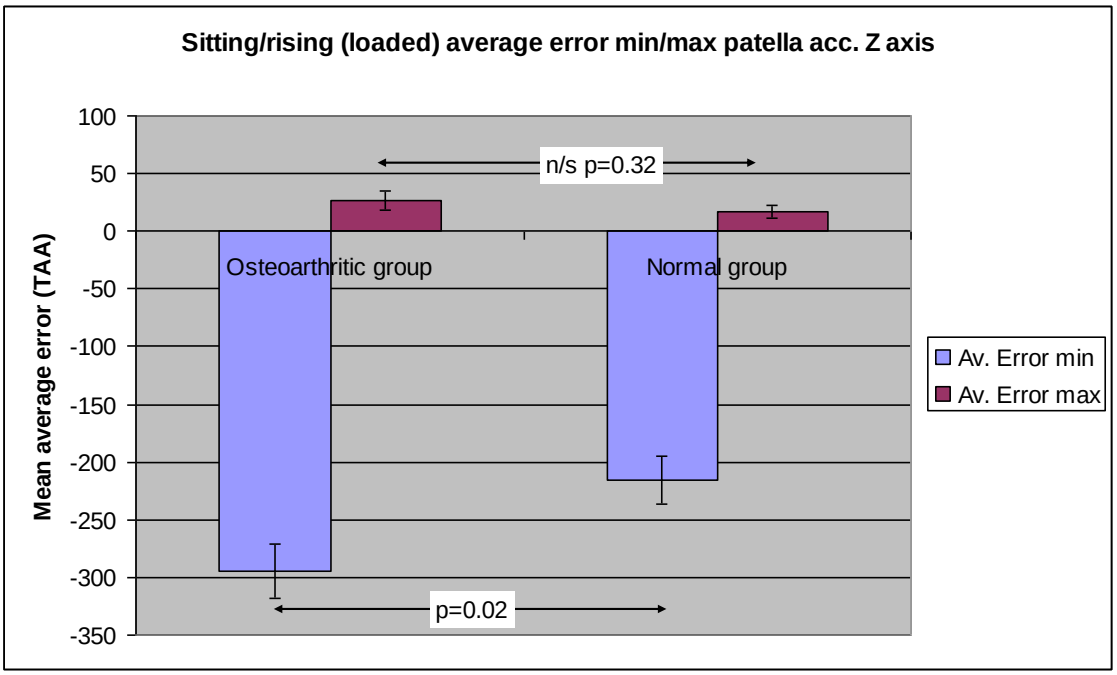


Figure 86. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, Z axis of the patella accelerometer.

The preceding figures 81-86 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the sitting/rising (loaded) protocol.

For the sitting/rising protocol patella accelerometer significant differences are found in the % error minimum values for X axis alone and this shows a lower value for the osteoarthritic group than the normal group, in effect the opposite of the previously described general downward shift observed in previous protocols. The average error minimum values for both the Y and Z axes are significantly different between the osteoarthritic and normal groups. These follow the same downward shift of suppression of the vibration signal as seen in previous protocol groups. There is no significant difference between means for the %/average error maximum values across all axes. broadly described the results for the Y and Z axes follow the pattern seen in the previous protocol groups, in that there is a downward shift between the osteoarthritic affected knee group and the normal knee group with higher values for both average error minimum and % error minimum in the osteoarthritic group and corresponding smaller values for the average error maximum and % error maximum.

Whilst the Z axis values are very similar to the results found for the walking protocol, the Y axis has experienced a shift in the values with greater values being recorded for % and average error minimum than those for % and average error maximum.

Most notable are the results for the X axis, these show results with greater values for the % and average error maximum and smaller for % and average error minimum in the osteoarthritic affected group compared with the normal group. This represents an upward shift in values for the osteoarthritic affected group when compared to the normal group, the outcome of this being the observation of an opposite effect to that found in all other results described so far. In effect the vibration signals for the osteoarthritic affected knee group are of greater magnitude than those for the normal group.

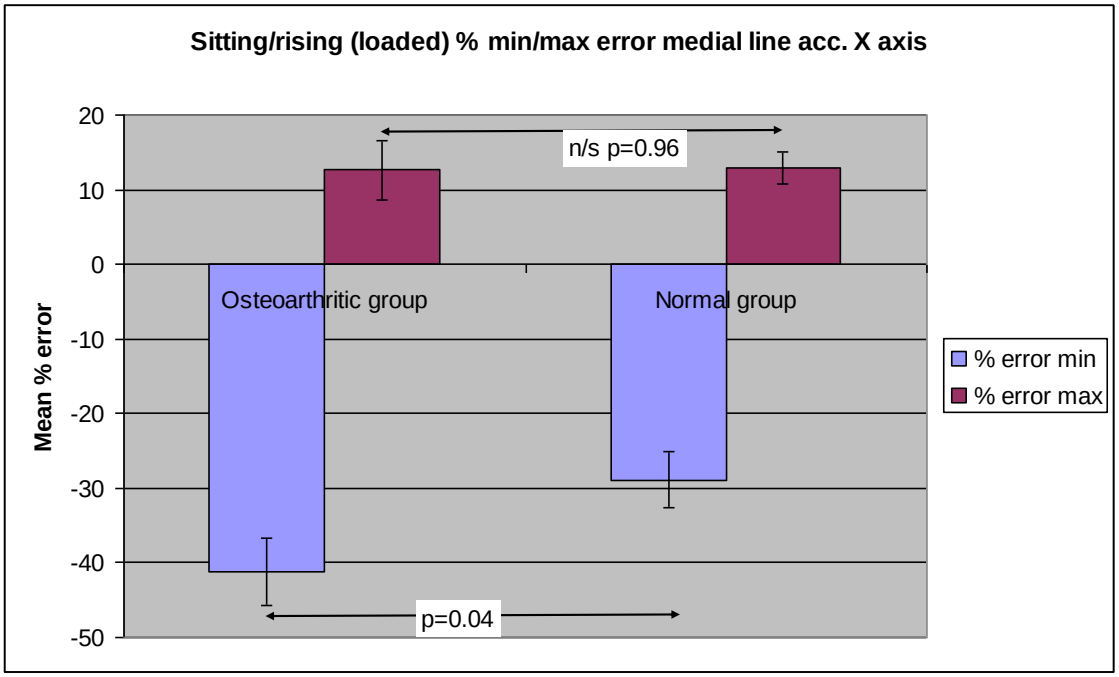


Figure 87. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, X axis of the medial line accelerometer.

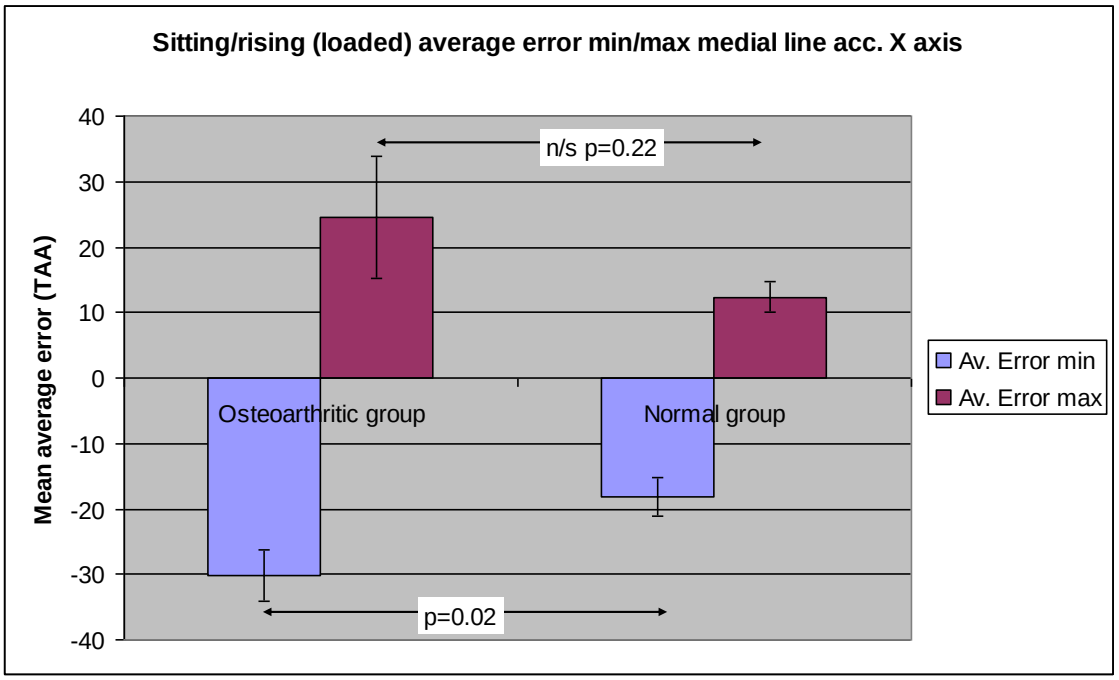


Figure 88. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, X axis of the medial line accelerometer.

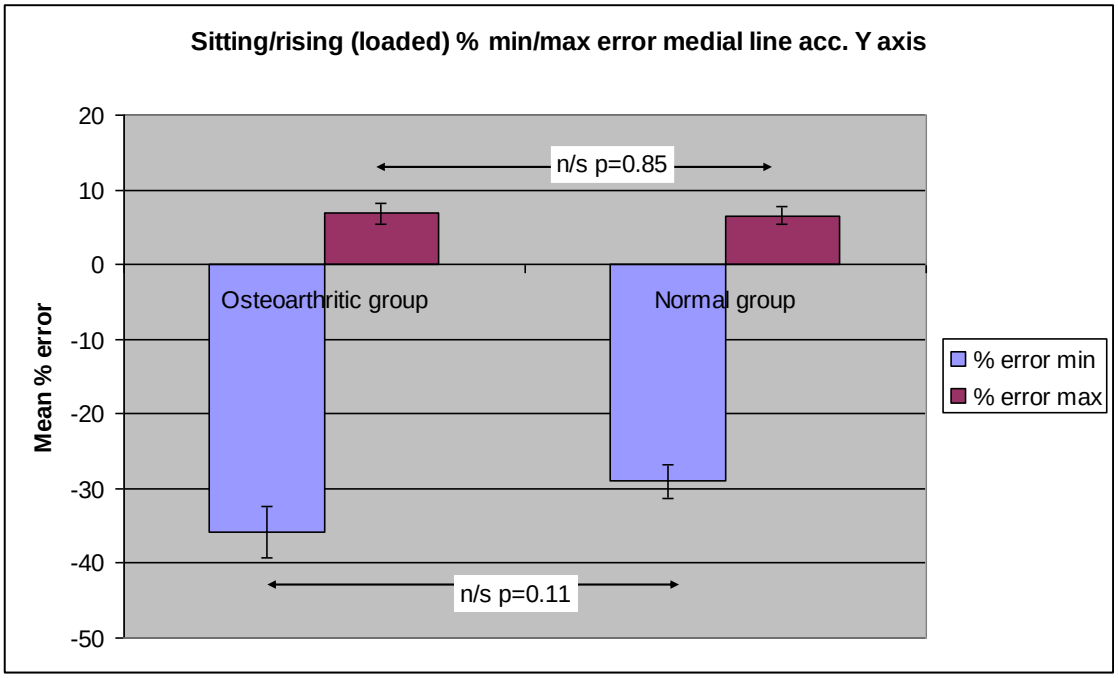


Figure 89. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

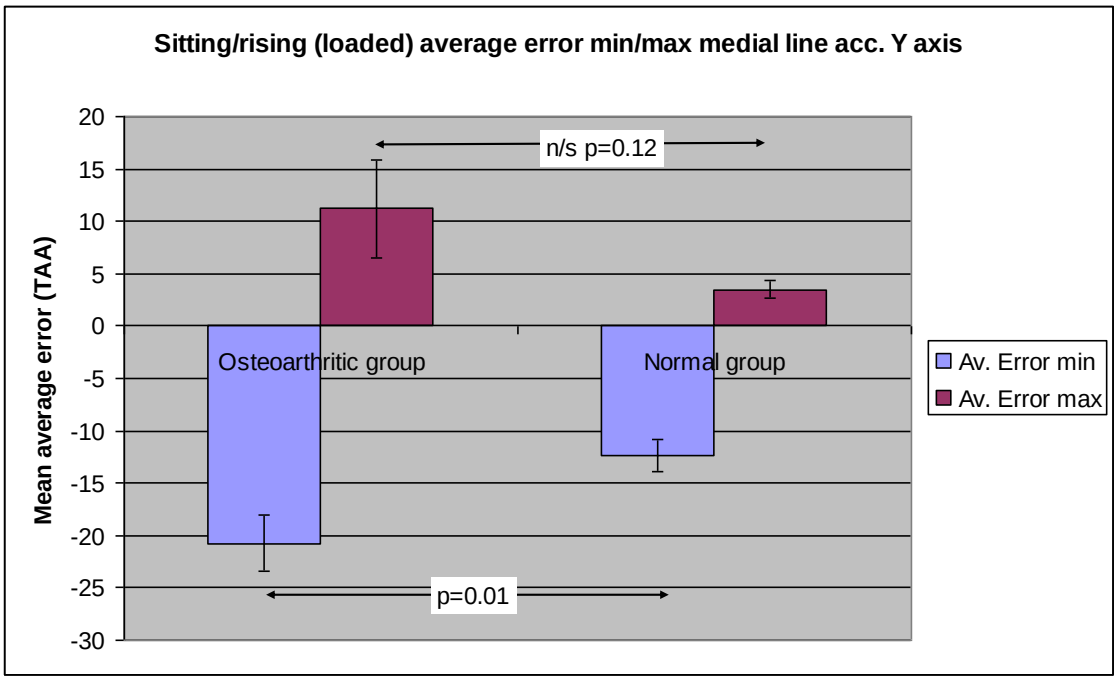


Figure 90. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, Y axis of the medial line accelerometer.

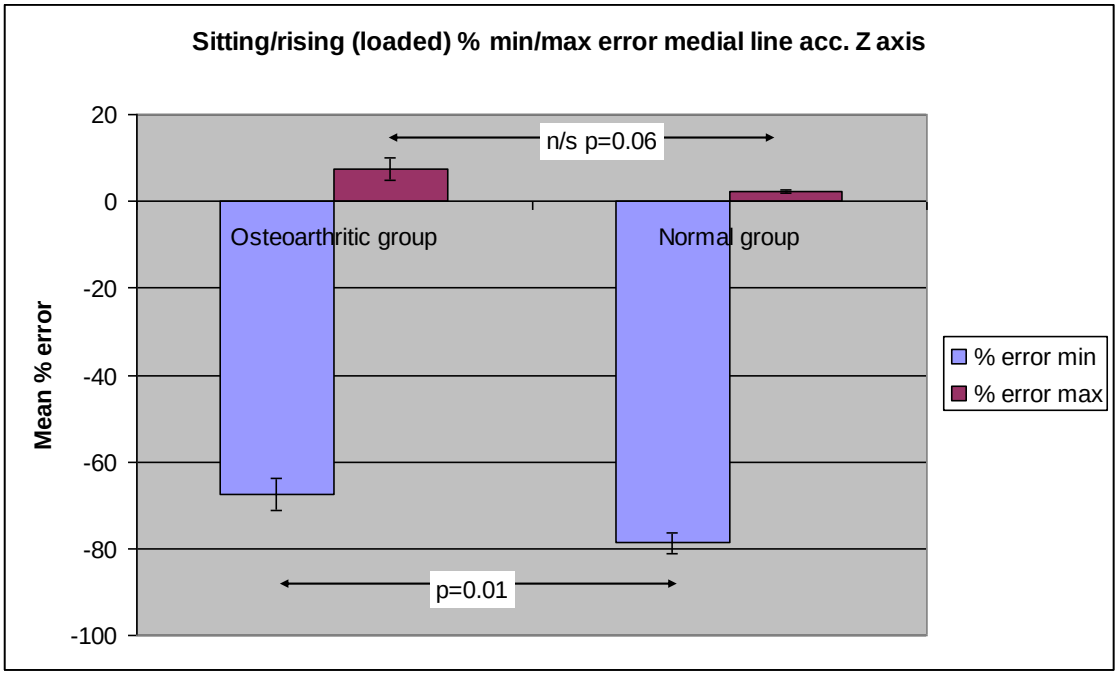


Figure 91. Mean values for sitting/rising (loaded) % min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

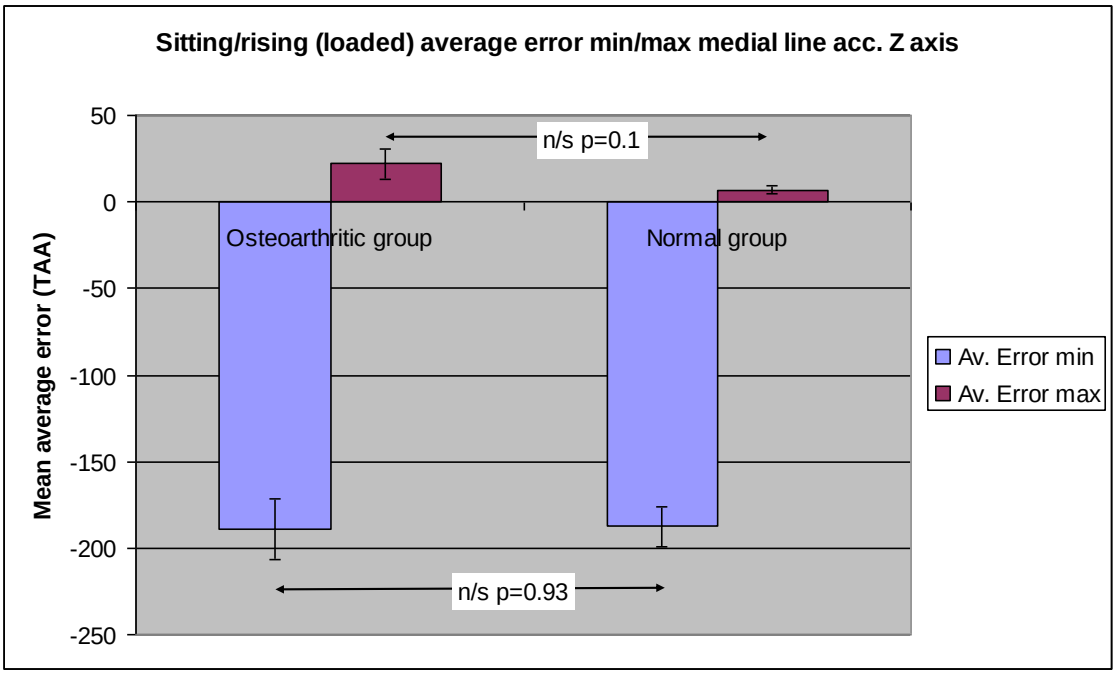


Figure 92. Mean values for sitting/rising (loaded) average min/max error, OA vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 87-92 show mean values for % error and average error for the osteoarthritic affected knee group and the normal knee group. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the sitting/rising (loaded) protocol.

The results for the X and Z axes of the medial line accelerometer show significant difference between osteoarthritic affected and normal group for the % error minimum values, the values for X axis % error minimum are greater for the osteoarthritic group suggesting a level of suppression, the Z axis however, shows the opposite effect with an upward shift in values .

The results for the X and Y axes of the medial line accelerometer show significant difference between osteoarthritic affected and normal group for the average error minimum values, in both axes the values are greater for the osteoarthritic group than the normal, suggesting a level of suppression.

All % and average error max results showed no significant difference in recorded mean values.

5.24: Discussion

The results as presented in the preceding section show evident differences between the osteoarthritic knee joint and normal knee joint group data. All protocol groups included significant results the majority being in the error minimum values. Within the data this manifests itself as a downwards shift in the values recorded for the osteoarthritic group when compared to the normal group, this in itself represents a level of suppression of the recorded vibration signal in the osteoarthritic group. The pattern of suppression is observable in all protocol groups and for both accelerometer positions although there are differences in the degree of significance to which these are found.

From the binary nature of the significant results it can be conclude that there is a difference between the vibration signal collected for an osteoarthritic knee and a normal knee joint thus proving the hypothesis that an osteoarthritic knee joint will produce a quantifiably different vibration response to a normal knee joint within the limitations of the number of individuals examined.

The fact that the difference between normal and osteoarthritic signals is manifested as a suppressed signal in the osteoarthritic knee joint is in itself interesting. It could be theorised that an osteoarthritic joint would produce a greater level of vibration signal and that the joint would be in effect louder due to the increased friction within the joint as the cartilage is worn away, this is clearly not the case. Since other biometric factors such as participant weight, age etc are taken into account within the sample groups tested it is probable that this difference is due to factors within the transmission pathway of the signal through the joint. It can be theorised that factors such as damage and inflammation of the articular surfaces of the joint or excessive fluid within the joint capsule could be the cause. Such factors could increase the distance of the signal transmission pathway within the joint as well as interfering with the actual signal in effect dampening it and resulting in the suppression seen. What is undeniable is that even if the exact cause has not been ascertained there is a clear readable difference between the healthy normal and osteoarthritic knee joint readings.

One further observation of note is that the most acute vibration signal results were found in the Z axis of the accelerometers. The Z axis values were generally higher for % and average error minimum than those for the X and Y axes and showed greatest differentiation from the normal control group data, suggesting that this channel recorded the strongest vibration responses from the knee. This corresponds well with similar results found by Abbott (2008) which found that vibration response was maximised in the Z axis of the patella accelerometer.

Within the protocol types there are observable differences, most notably between the unloaded protocol and the loaded protocols. All groups show a general pattern similar to that already described (suppression in the osteoarthritic group).

Within the walking protocol (loaded) group there is an observable trend towards generally higher values for the error maximum values in the X and Y axes this suggests that for these axes the signal recorded is generally higher than equivalent axes in unloaded joints. This could be ascribed to the increased level of pressure being found in the loaded knee joint causing more contact and friction between the bones of the joint. The Z axis however, shows a greater level of suppression, one theory that could explain this is that the greater pressure from the loaded joint is causing additional lubrication within the joint via the effects of the dynamic lubrication regime as proposed by Mow (1977). Neither explanation is entirely satisfactory as they appear contrary to each other in relation to the effected axes. It should be noted however, that these observations in relation to the loaded are seen in both the normal and osteoarthritic joint groups.

The sitting/rising protocol (loaded) show results that although with the least number of significant results, include examples where the pattern of suppression is reversed with a greater signal output for the osteoarthritic group than the normal (notably the patella accelerometer X axis and medial line accelerometer Z axis). The sitting/rising protocol also includes examples whereby the joint signal is both greater and lesser than the normal group; in effect the spread of the recorded signal is greater on both sides of the prediction corridor. These results suggest that the signal is a poorer fit to the prediction than the normal and that the system is experiencing calibration problems with this data.

One tentative additional clue to these effects is that the processing of data by the phonoarthrometer software produced more viable results for the swing (unloaded) protocol than the walking or sitting/rising (loaded) protocols. This is due to generally longer sequences of flexion/extension being identified in the swing (unloaded) protocol signals than for the walking and sitting/rising (loaded) protocols, with the software being able to analyse the longer sequences found in the swing (unloaded) data better.
One further factor could be due to the use of a microstructure library that was constructed using the swing (unloaded) protocol to analyse walking and sitting/rising (loaded) recording. The use of a microstructure library constructed purely from swing protocol readings could result in those microstructure types as stored in the database not fully encompassing the microstructure found in the flexion/extension sequences found in the walking and sitting/rising vibration signals.

5.25: Generation of values for sensitivity and specificity.

The binary nature shown in the results of the analysis of the osteoarthritic group when compared to the normal group gives an early indication that the phonoarthrometer can be evaluated to some degree as a diagnostic tool.

As an example of this the following preliminary evaluation was carried out. To do this a particular measurement parameter was chosen from the proceeding graphical outputs. The choice of this parameter was based on a number of factors. In the first instance the flexion swing protocol was chosen, as this protocol type produced by far the most processed data and was the most stable for software operation.
Secondly a highly statistical significant result was chosen as this should result in a good differentiation between the osteoarthritic and normal values selected.
Finally consideration was given to placement errors that could be incurred in the dataset from a misaligned accelerometer as shown in chapter 4.

Values for both % error minimum and average error minimum, from the patella accelerometer Y axis, were selected as the measurement parameter to be tested. In the preceding analysis the patella accelerometer Y axis produced a result that showed highly significantly differences ($p<0.0001$) between the normal and osteoarthritic group tested for both % error min and average error min with a good separation range between the

recorded data values. In addition standard error for the dataset was also relatively small suggesting that the values were relatively stable around a mean value.

The final consideration was a compromise as although the Y axis was shown to be the most sensitive when incorrectly placed; such misplacement resulted in deviations largely in increases to the maximum error values. However, since the general pattern of osteoarthritic change results in a suppression of the recorded values such misplacement would result in obvious anomalies in the data values if the accelerometer had been misplaced. The values for the Y axis in the preceding results show a strong level of suppression indicating that negligible error was introduced in the dataset by misplacement of the accelerometer.

Following on from this all the patella accelerometer, Y axis, minimum % and average error mean values were extracted for each individual participant from the osteoarthritic and normal groups. These were then plotted as individual points for each group (OA/normal), shown in the following two graphs (figures 93 and94).

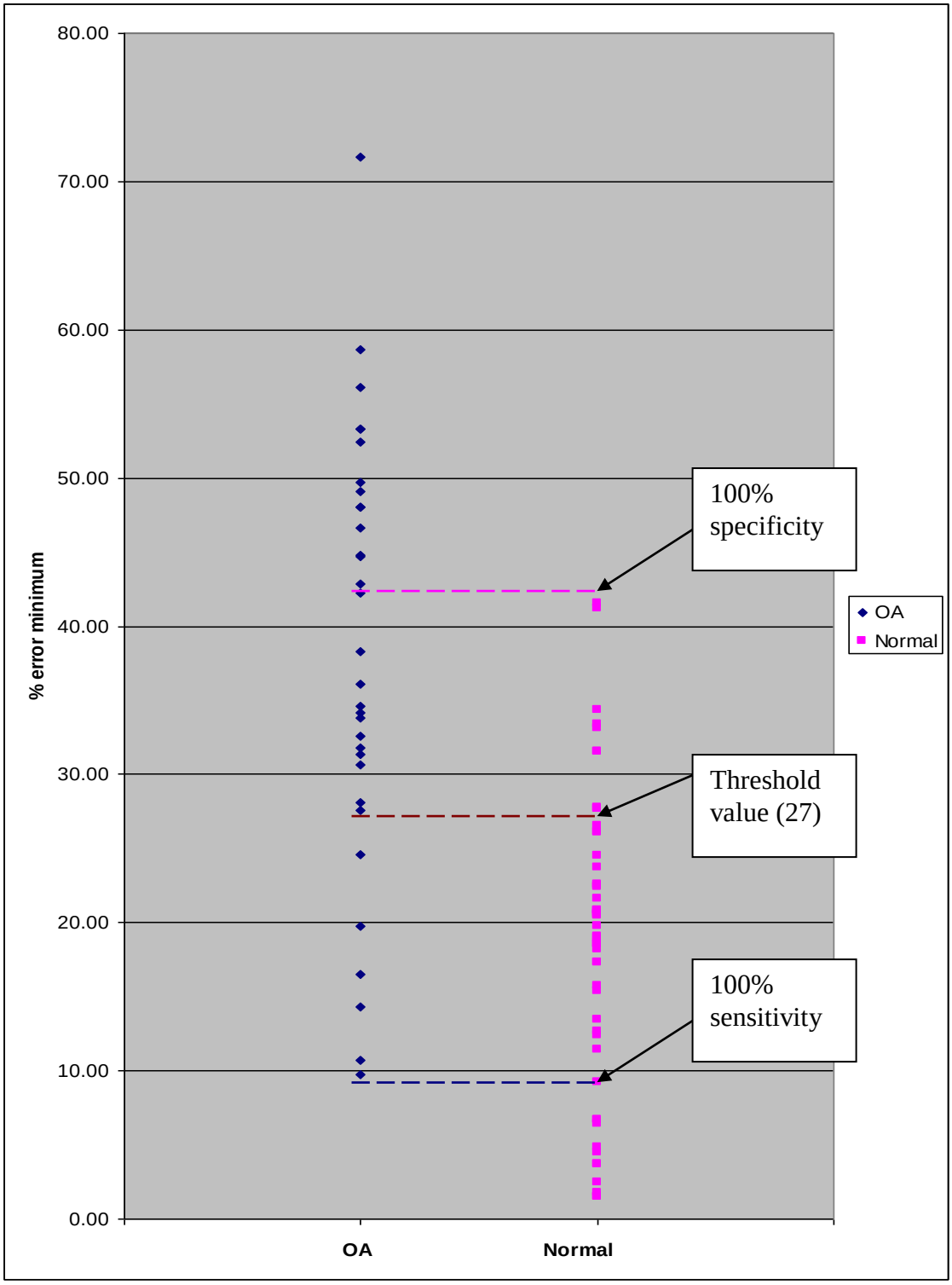


Figure 93. Mean % error minimum values from the patella accelerometer Y axis for each individual participant from the osteoarthritic group versus individual participants from the normal group.

The above graph (figure 93) shows % error minimum values for individuals from the osteoarthritic and normal groups.

Lines representing various threshold % minimum error values are shown on the graph.

The upper line (pink) shows the threshold for 100% specificity, in this instance set to a value of 42 (%) error minimum. At this value all normal knees are correctly identified (true negatives) and the number of incorrectly diagnosed normal knee joints (false positive) is zero.
Setting the threshold at this value results in a sensitivity value of 47% , meaning that only 47% of osteoarthritic knees are correctly identified (true positives) and 53% of the osteoarthritic knees are wrongly diagnosed as being healthy (false negatives).

Conversely the lower line (blue) shows the threshold for 100% sensitivity corresponding to a value of 9 (%) error minimum. At this threshold value all osteoarthritic knees are correctly identified as being osteoarthritic, no false negatives are found. However, as before there is a trade off and specificity is reduced to 21%, meaning that only 21% of normal knees are diagnosed as healthy. In this case 79% of all normal knees would be wrongly diagnosed as osteoarthritic.

The middle line (dark red) indicates a threshold value of 27 (%) error minimum. The setting of this threshold value is intended to maximise specificity and sensitivity values. Setting the threshold at the 27% error minimum value produces a specificity value of 82% and sensitivity value of 81%. At this threshold 82% of normal knee joints are correctly classed as healthy and 81% of osteoarthritic knee joint are correctly diagnosed as osteoarthritic.

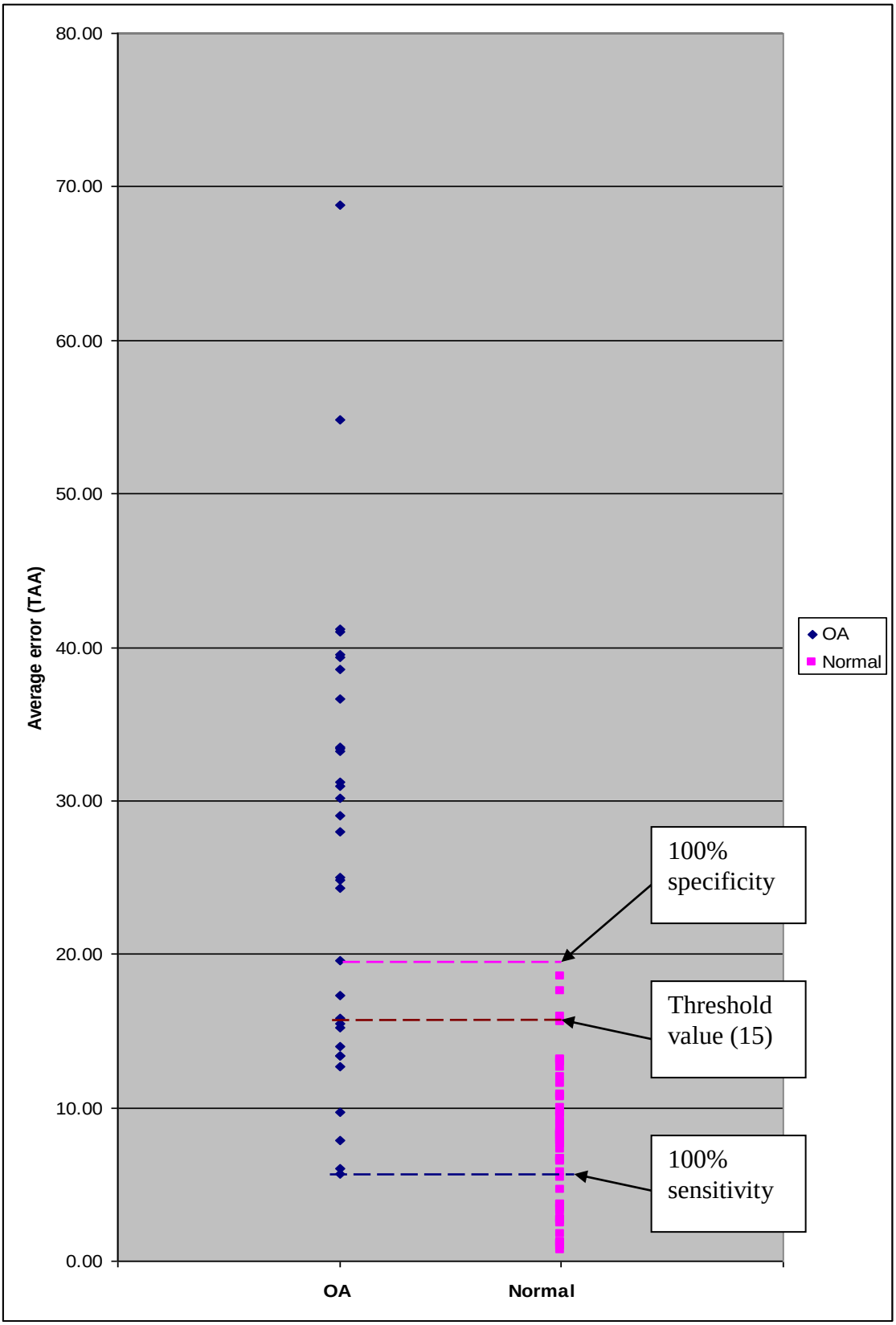


Figure 94. Mean average error minimum values from the patella accelerometer Y axis for each individual participant from the osteoarthritic group versus individual participants from the normal group.

The above graph (figure 94) shows average error minimum values for individuals from the osteoarthritic and normal groups.
Lines representing various threshold average minimum error values are shown on the graph.

In the same way as the preceding figure (93) the upper line (pink) corresponds to the threshold for 100% specificity, this value was set at 19 (TAA) average error minimum. At this threshold value all normal knee joints are correctly identified as healthy (no false positives) .Setting the threshold at this value results in a sensitivity value of 64%, in effect 64% of osteoarthritic knee joint were correctly identified.

The lower line (blue) shows the threshold for 100% sensitivity as set at a value of 5 (TAA) error minimum. At this threshold value all osteoarthritic knees are correctly identified and no false negatives are found. However, as before there is a trade off and specificity is reduced to 29% meaning only 29% of the normal knee joints are correctly classified as healthy and 71% are wrongly diagnosed as osteoarthritic.

As before a threshold was selected in an attempt to maximise specificity and sensitivity values. The middle line (dark red) denotes the selected threshold value of 15 (TAA). This threshold results in values for specificity of 92% and sensitivity of 75%. So at this threshold value 92% of normal knee joint will be classified as healthy and only 8% will be wrongly diagnosed as osteoarthritic. 75% of the osteoarthritic knee joints will be correctly diagnosed and 25% will be incorrectly labelled as healthy.

The ability shown here for a testable threshold value to be set and the use of this to produce viable sensitivity and specificity values is a positive step in the development of the phonoarthrometer as a potential diagnostic tool for clinical usage in the diagnosis of osteoarthritis.

5.3: Comparison of medial/lateral compartment osteoarthritis data with normal knee joint group data.

The following section presents the data as a series of graphs showing the mean values of % min/max error and average min/max error for medial and lateral compartment osteoarthritic knee joint groups and the normal knee joint group. The medial and lateral compartment osteoarthritic groups were identified from within the main osteoarthritic group via use of the surgeon's notes. As for the main results the data is divided according to the protocol type performed (swing (unloaded), walking (loaded) and sitting/rising (loaded)) and according to the accelerometer position (patella or medial line) used to collect the vibration signal. Positive values denote % and average error maximum values, negative values denote % and average error minimum values in each case, in effect these represent the level of deviation for each group above (maximum) or below (minimum) the prediction corridor as produced following analysis of the vibration signal by the phonoarthrometer software. The values were plotted negatively for the minimum data in order to graphically represent % and average error falling below the prediction corridor. For each plotted data point error bars are shown, representing the standard error of the sample means from the data set. T test comparisons of the sample means were carried out for each error min/max dataset, with the significance level set at $p<0.05$. Statistical significance is shown on the graphs using a lettering method (Bates College, 2012), results of the multiple comparisons are denoted by the assigned letters above each data point; means with different letters are significantly different. For the purpose of clarity the first two figures (95 and 96) have this annotation described as examples.

5.31: Swing (unloaded), medial and lateral osteoarthritic versus normal.

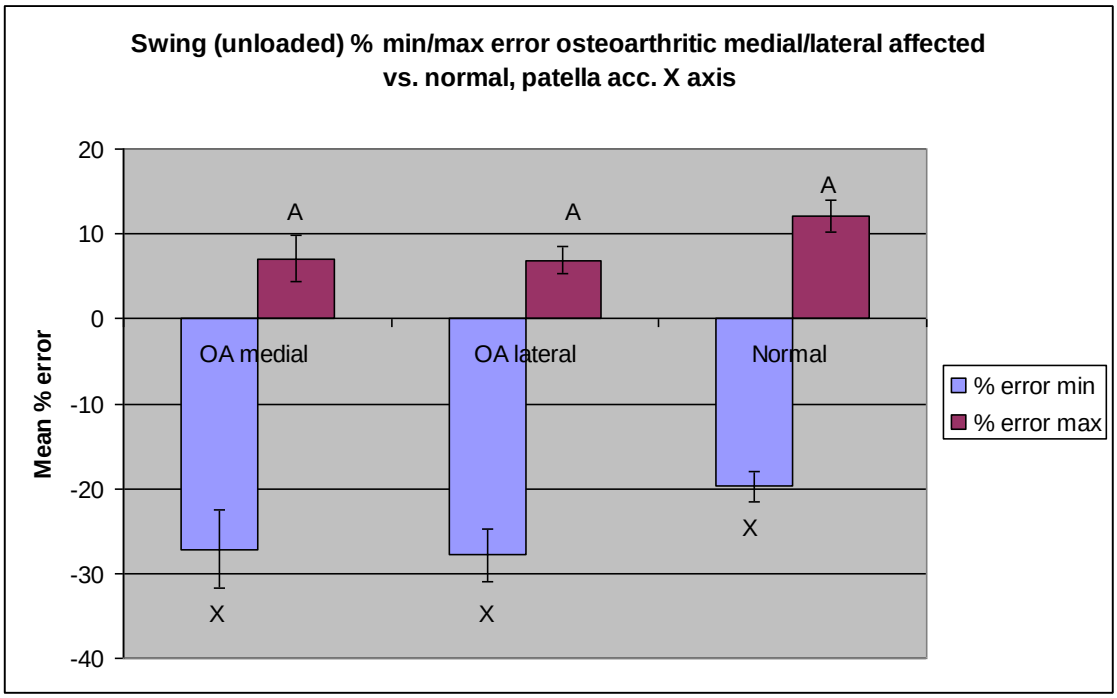


Figure 95. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

In this example all the maximum % error values are assigned the letter ‘A’ and as such there is no statistically significant difference between all three of the comparisons made (OA medial vs. OA lateral, OA medial vs. normal and OA lateral vs. normal). The minimum % error values show the same non-significant difference between each of the comparisons but are assigned the letter ‘X’ in order to differentiate them from the maximum % error values.

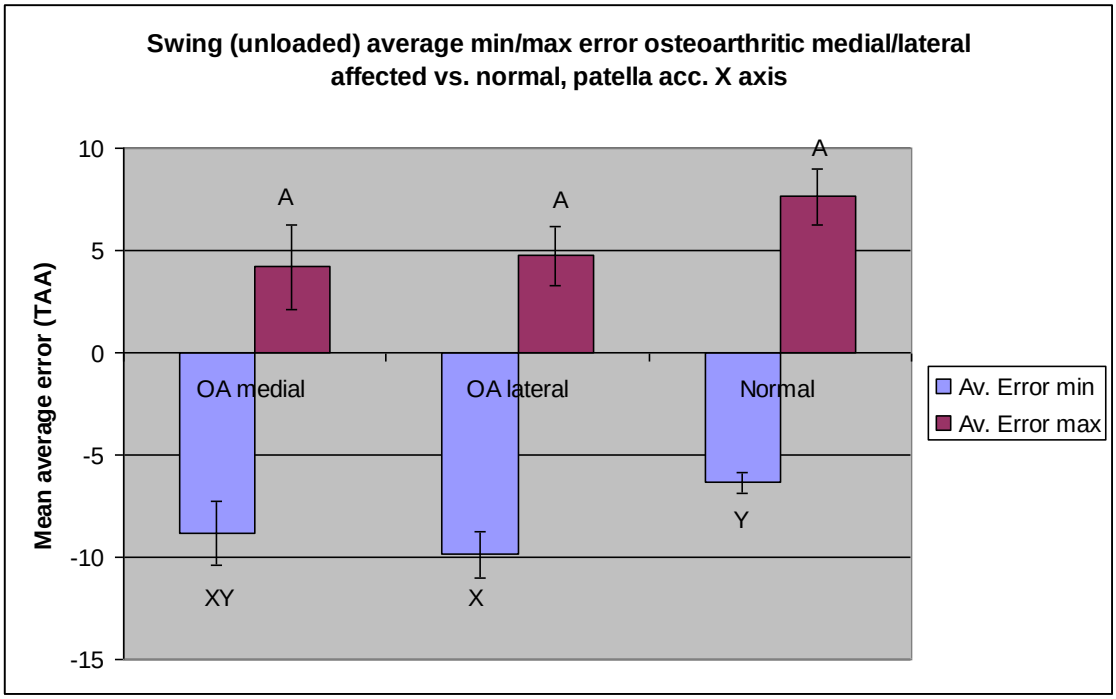


Figure 96. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

In this case all the maximum average error values have the same assigned letter (A) showing that there was no statistical difference between them in any comparison. For the minimum average error values however, the OA medial value has both X and Y assigned showing that it is not statistically different from either OA lateral or normal. The OA lateral value has only an X so whilst it is not statistically different from the medial it is from the normal value, in a similar manner normal has the letter Y assigned and so shows no statistical difference to OA medial but is significantly different from the OA lateral value.

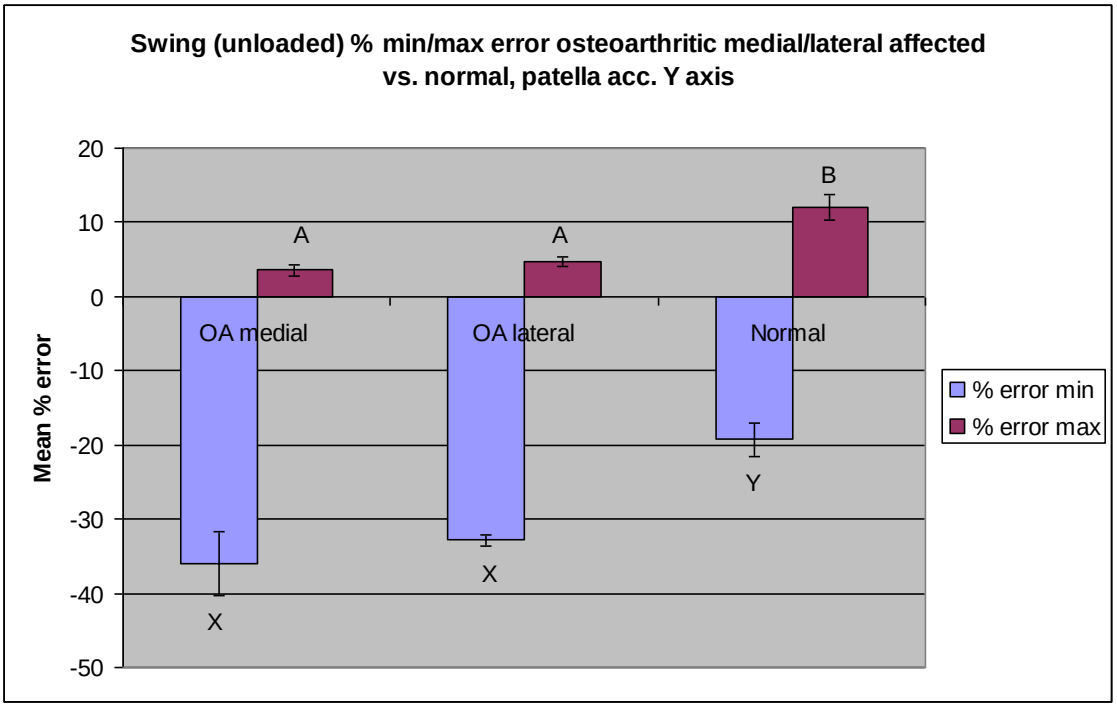


Figure 97. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

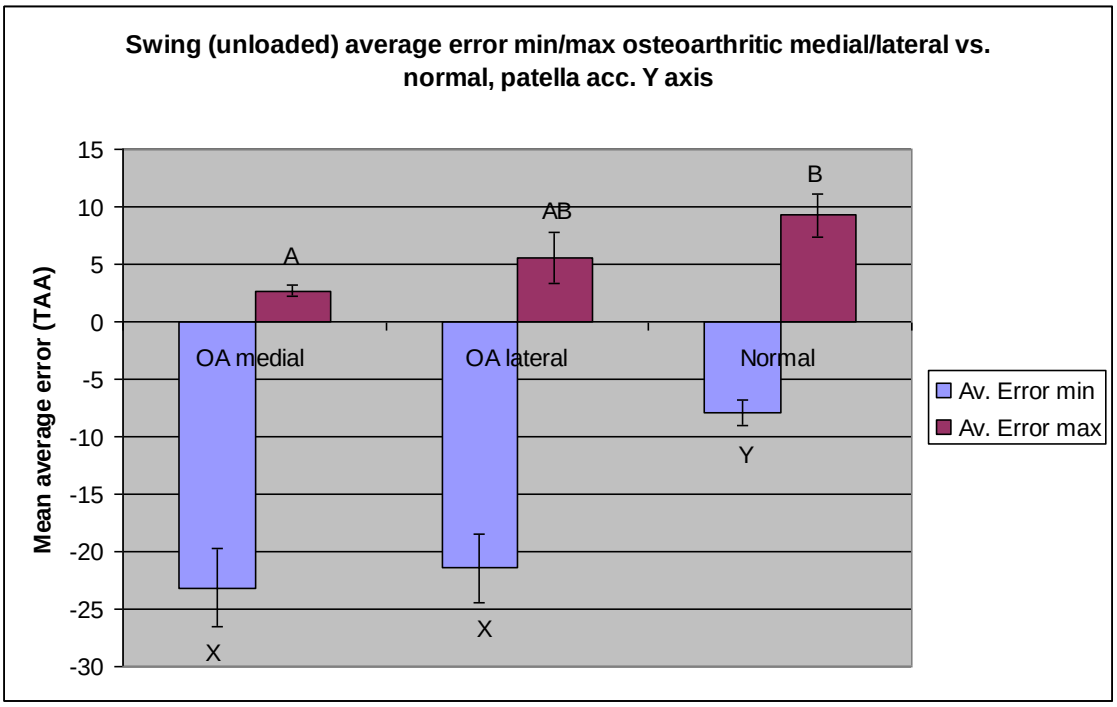


Figure 98. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

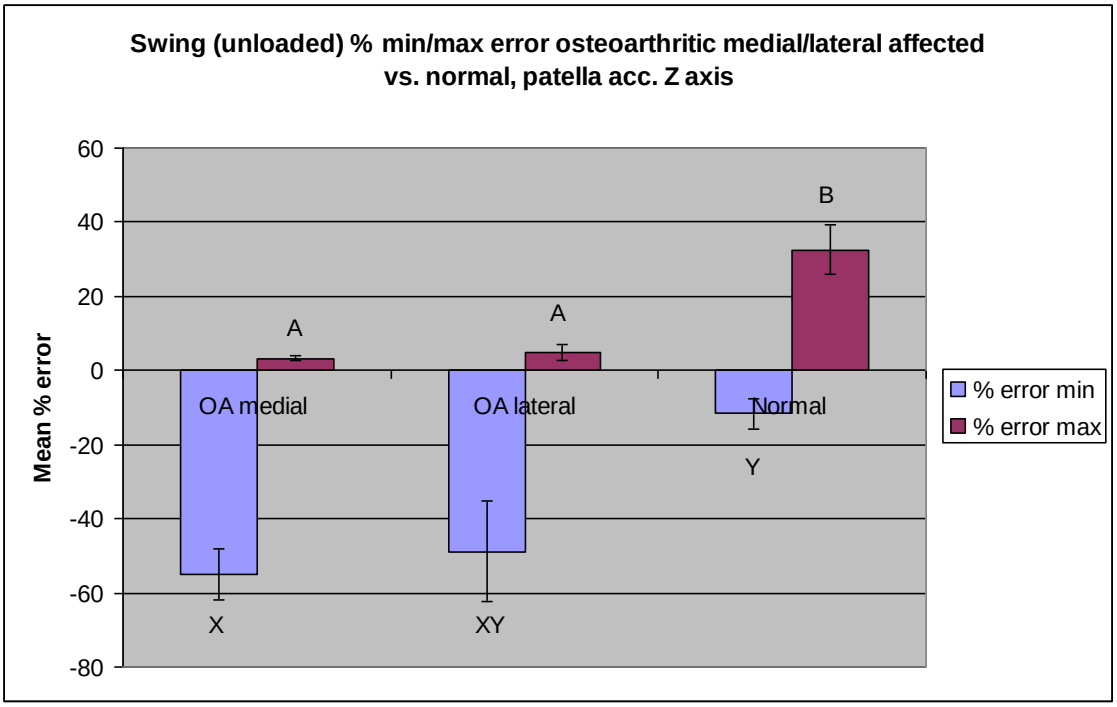


Figure 99. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

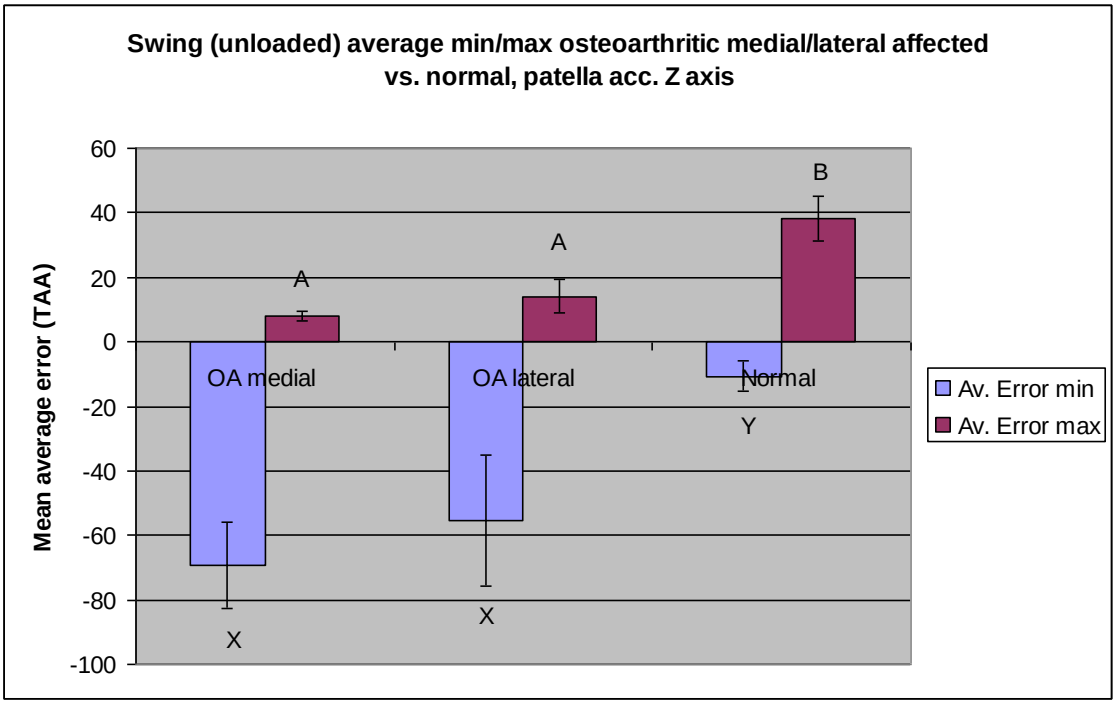


Figure 100. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

The preceding figures 93-98 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the swing (unloaded) protocol.

The X axis shows significantly different values for the average error minimum of the lateral and normal group.
The Y axis shows significant differences for both the lateral and medial group %minimum and %maximum error when compared to the Normal but no difference between the lateral and medial group. For average error both lateral and medial minimum values are different from normal and maximum average error is different to normal in the medial group.
The Z axis shows significant differences in the maximum % error for both medial and lateral groups compared to the normal minimum % error is different in the medial group from normal. The average error shows difference between medial/ lateral and normal in both minimum and maximum values. No difference is observed between the medial and lateral values
In all these examples the pattern of suppression of the osteoarthritic vibration signal when compared to normal is seen, as in the previous section.

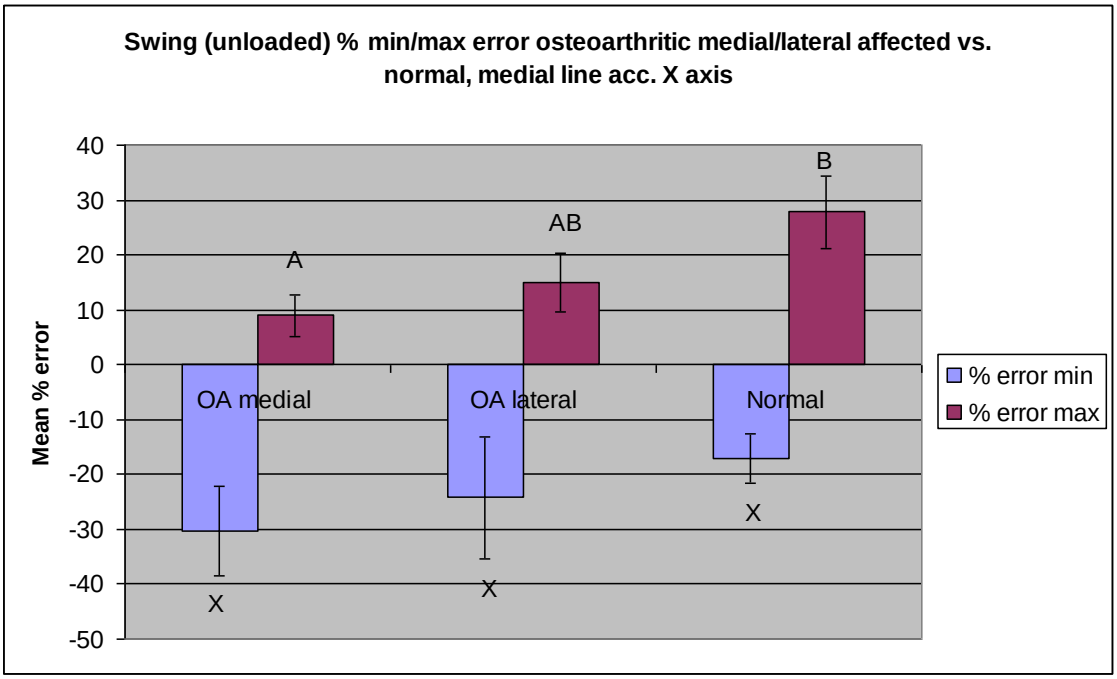


Figure 101. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

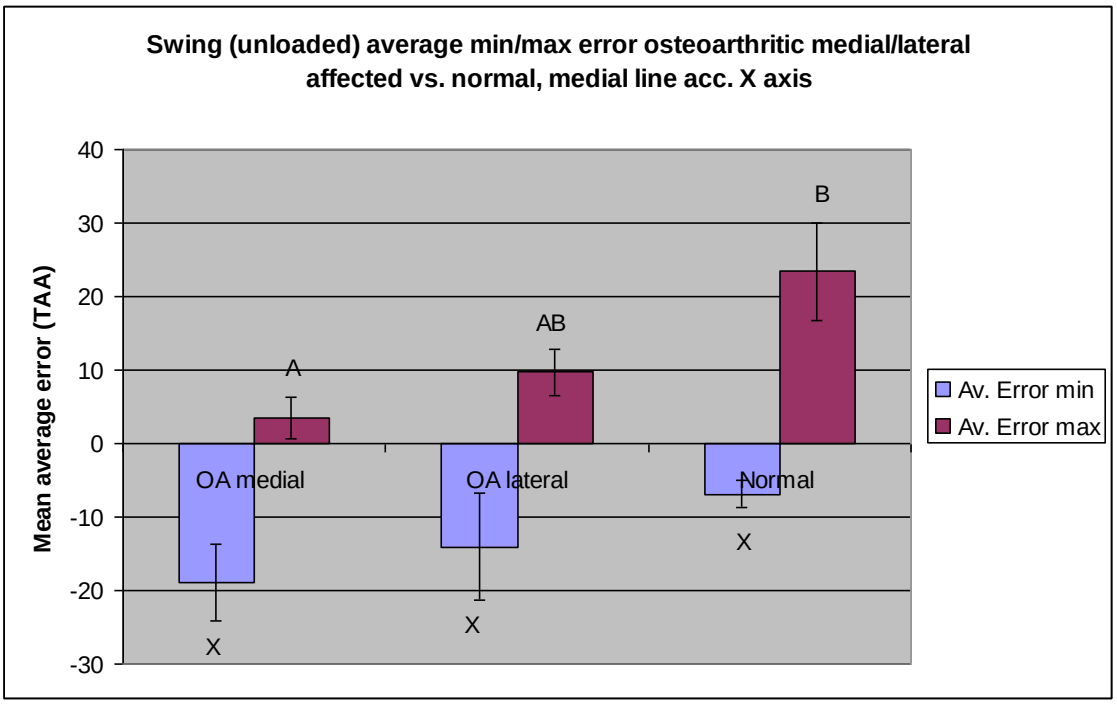


Figure 102. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

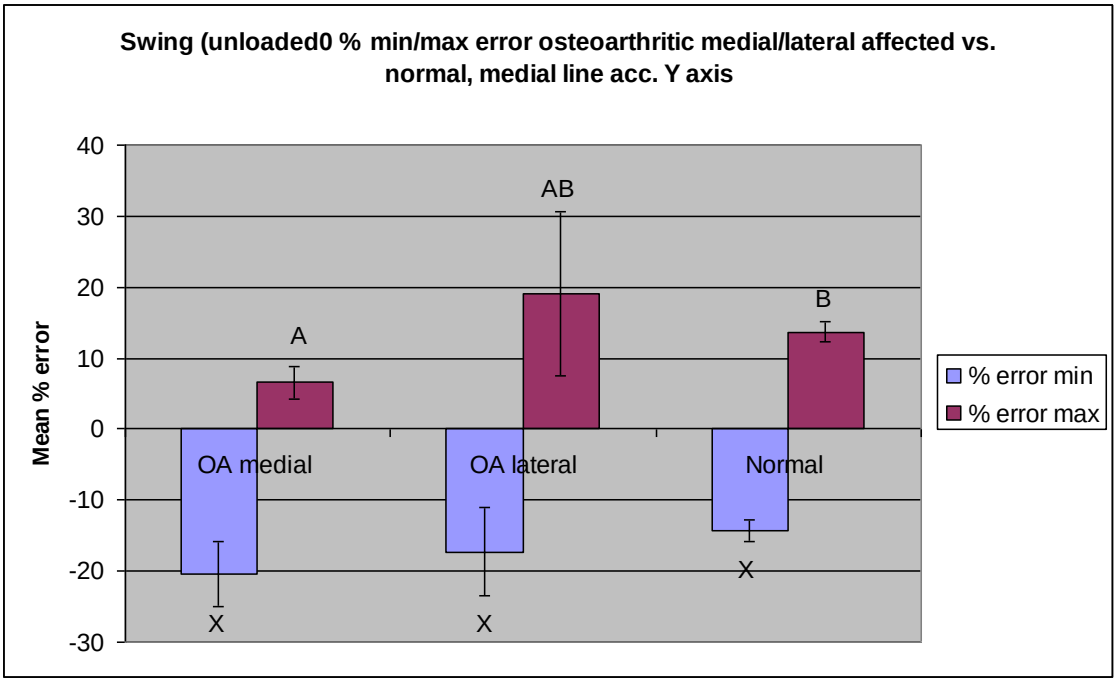


Figure 103. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

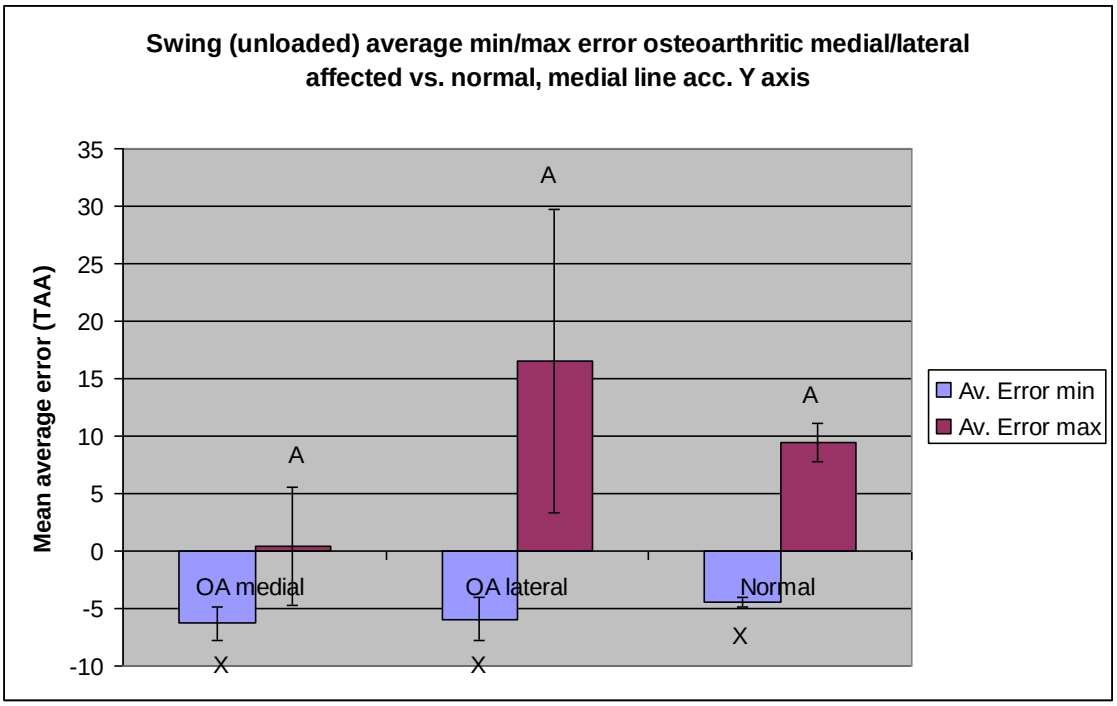


Figure 104. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

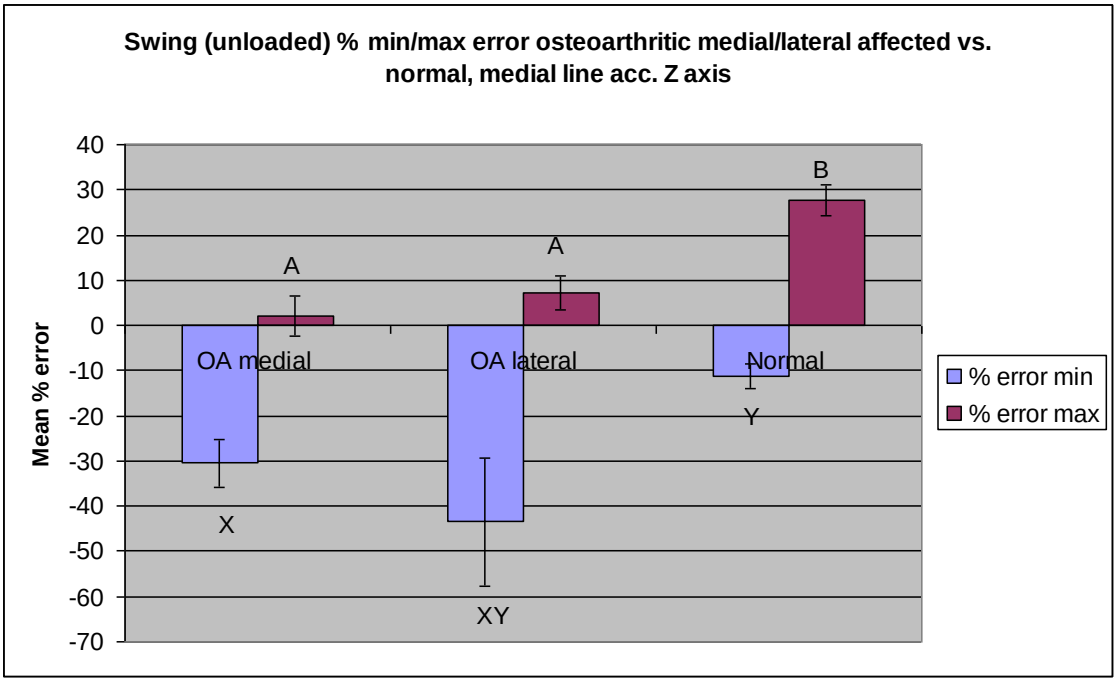


Figure 105. Mean values for swing (unloaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

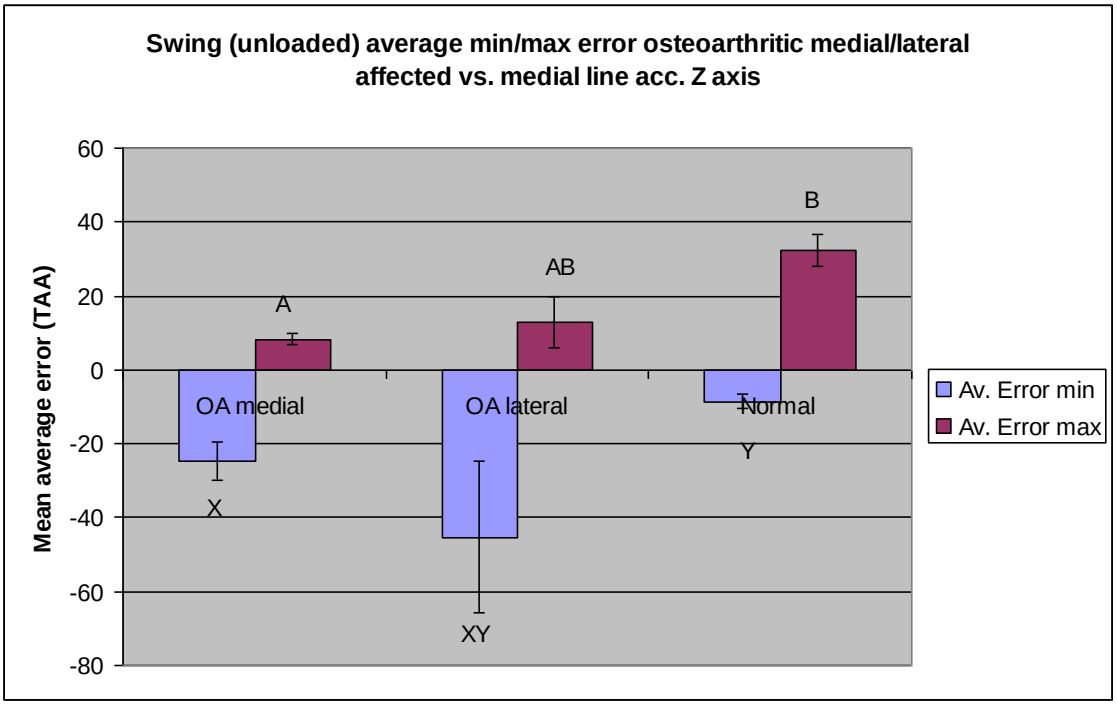


Figure 106. Mean values for swing (unloaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 101-106 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the swing (unloaded) protocol.

The X axis shows significant differences between the medial/lateral groups and normal for both % and average error minimum, the % and average error maximum was only significantly different from the normal in the medial group.

The Y axis only showed significant difference between the medial % maximum value and normal. The standard error of the lateral group maximum error values is high.
The Z axis shows differences between % error maximum for the medial/lateral groups and the medial % error minimum compared to normal. The medial group average error maximum and minimum differs from normal.

No significant differences are observed when the medial and lateral groups are compared.

5.32: Walking (loaded), medial and lateral osteoarthritic versus normal.

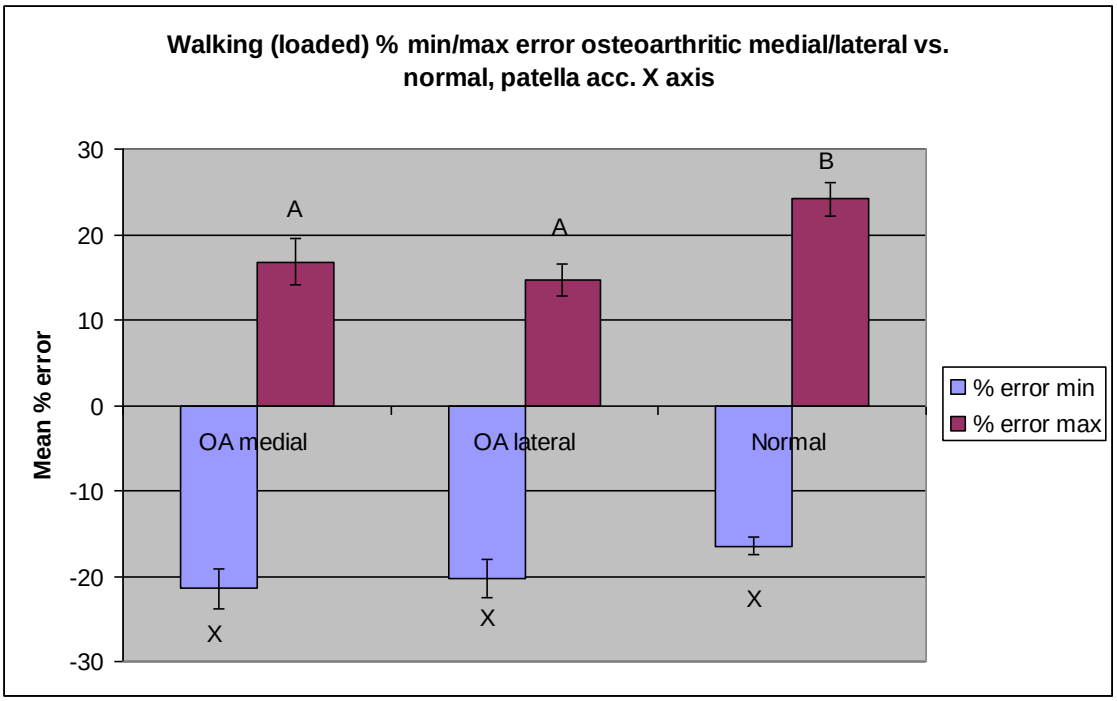


Figure 107. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

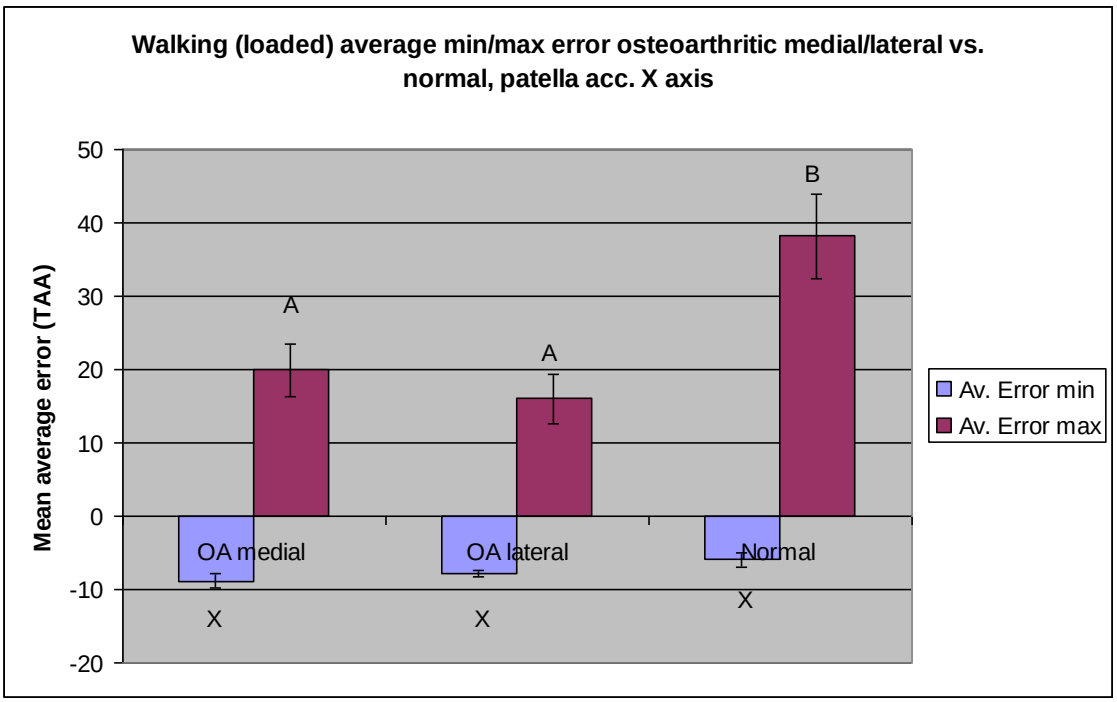


Figure 108. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

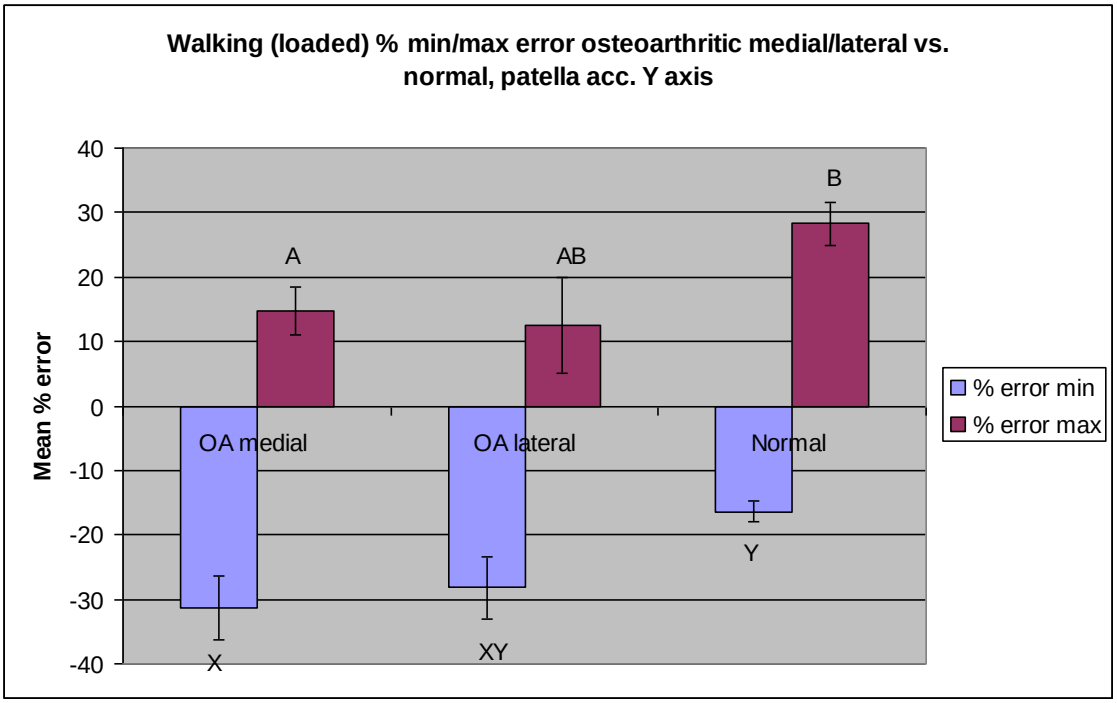


Figure 109. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

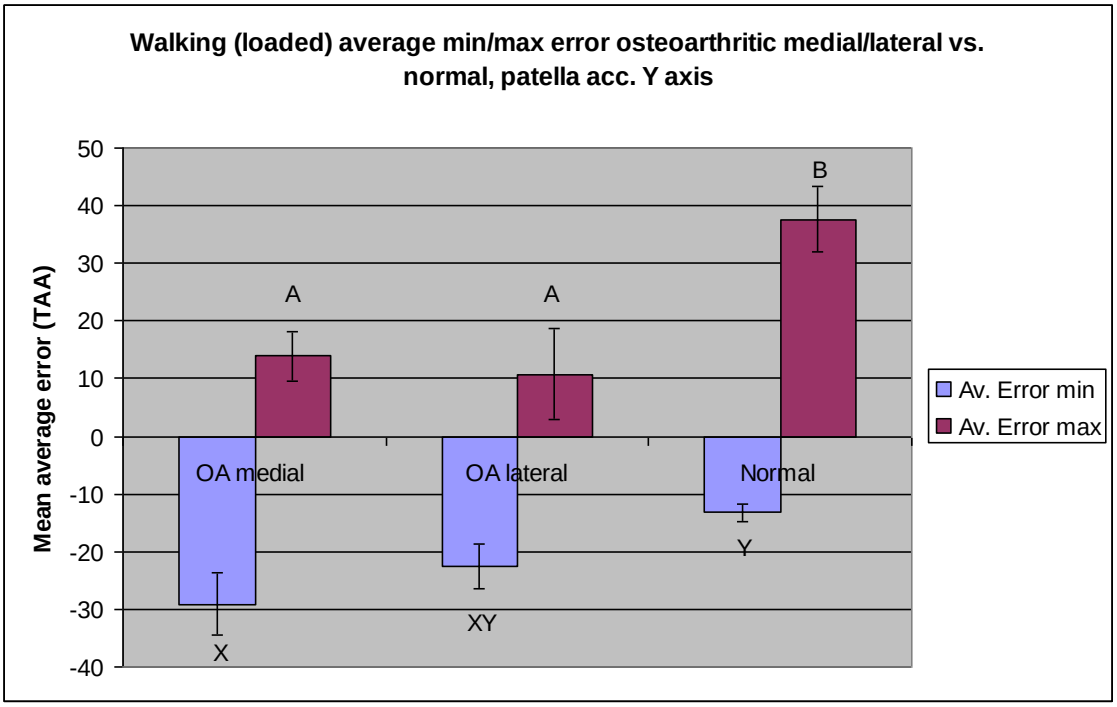


Figure 110. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

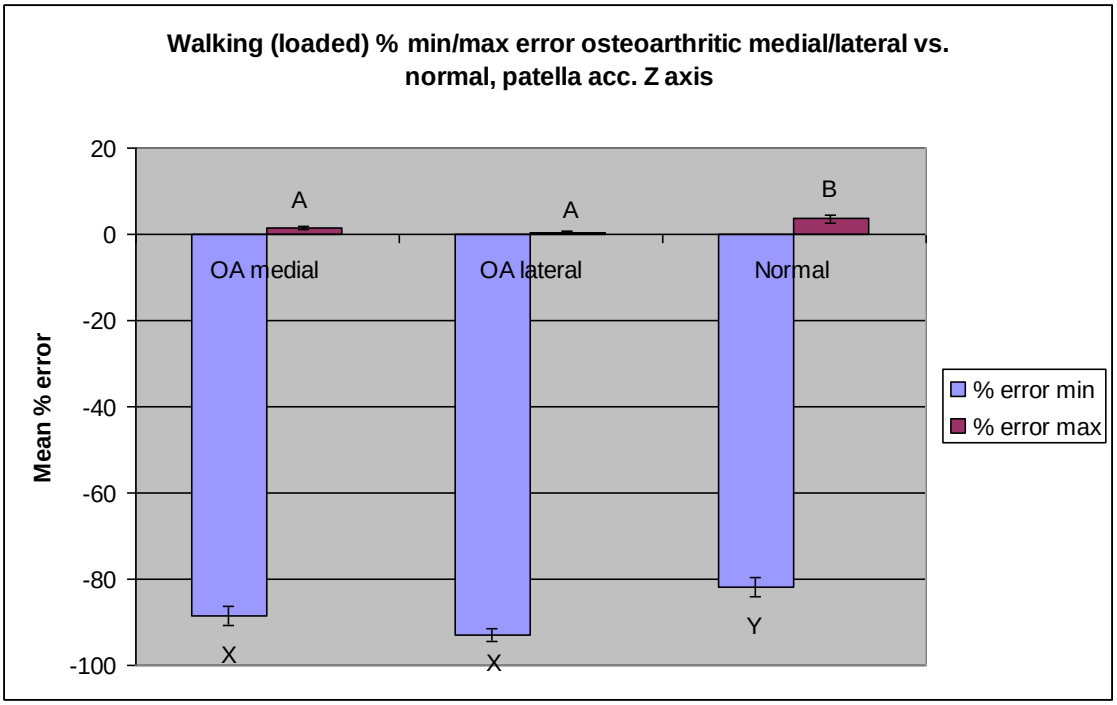


Figure 111. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

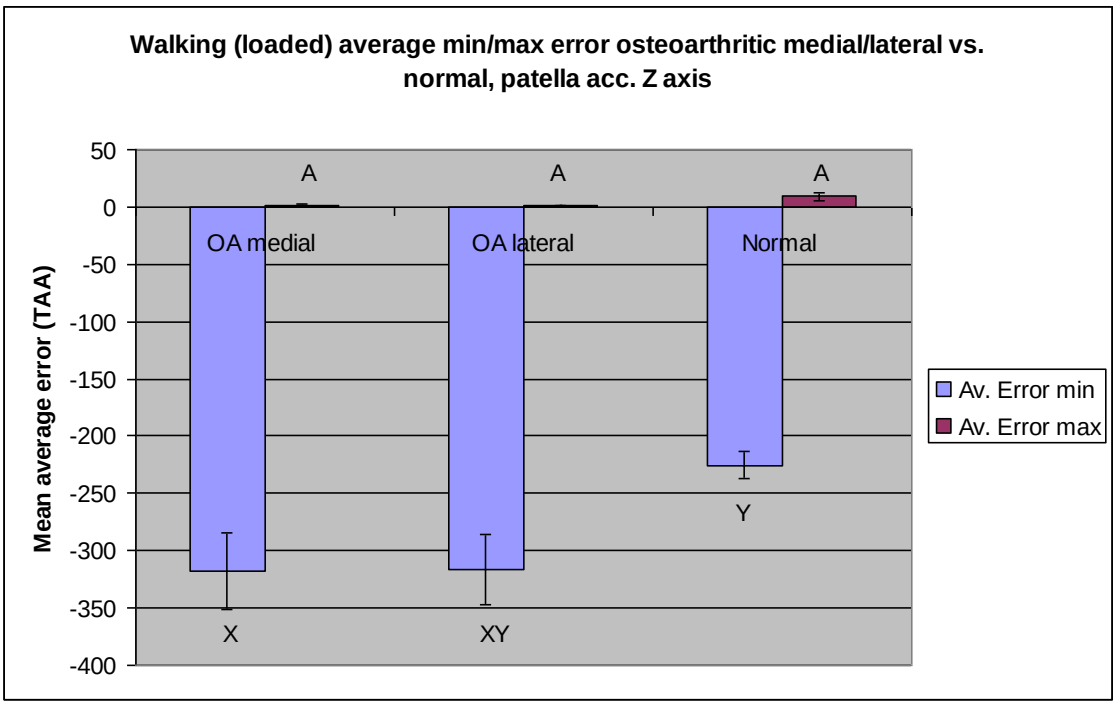


Figure 112. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

The preceding figures 107-112 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the walking (loaded) protocol.

The X axis values for both the medial and lateral groups are significantly different from the normal for % error maximum.
The Y axis show differences between the medial minimum and maximum % error values and that of the normal group, for average error both medial and lateral group maximum values differ form normal but only the medial minimum value differs from normal.
The Z axis shows differences from normal for both minimum and maximum % error for the medial/lateral groups. Average error values are only different between the medial minimum error and normal.
No significant differences were found between the medial and lateral groups.

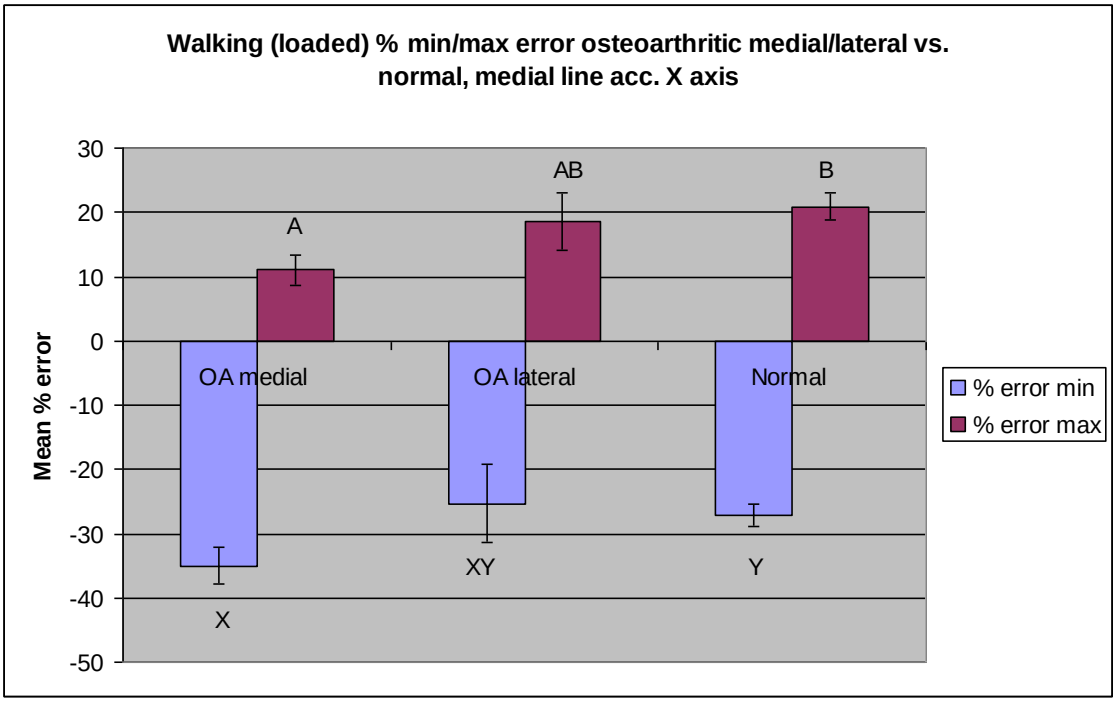


Figure 113. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

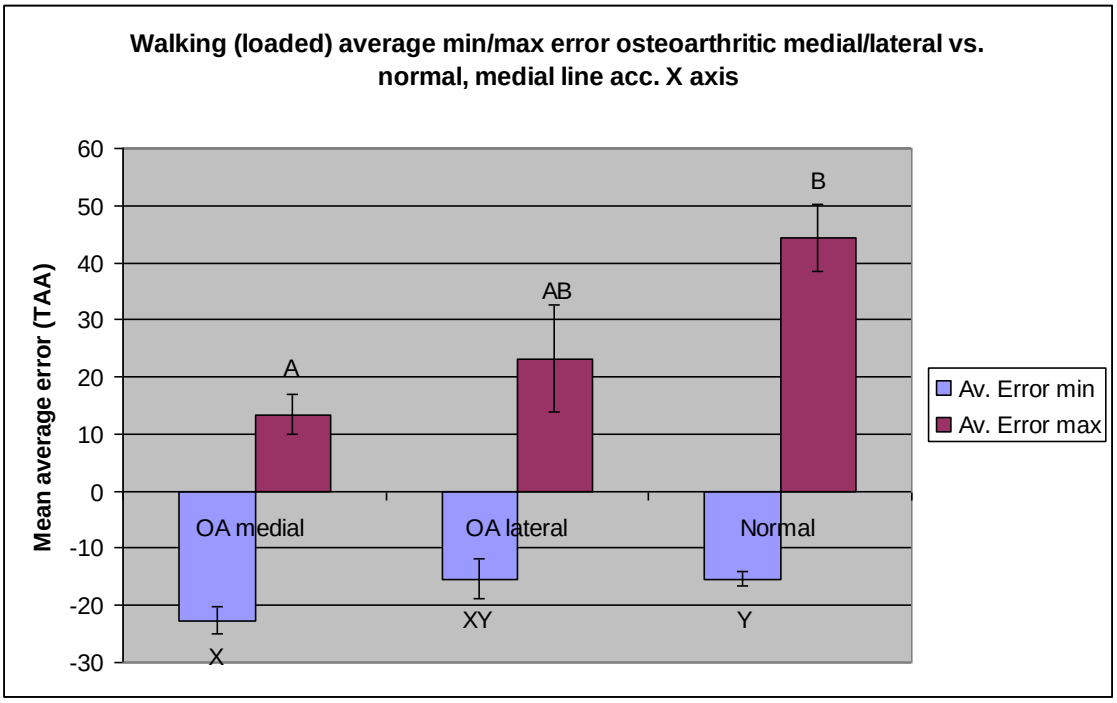


Figure 114. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

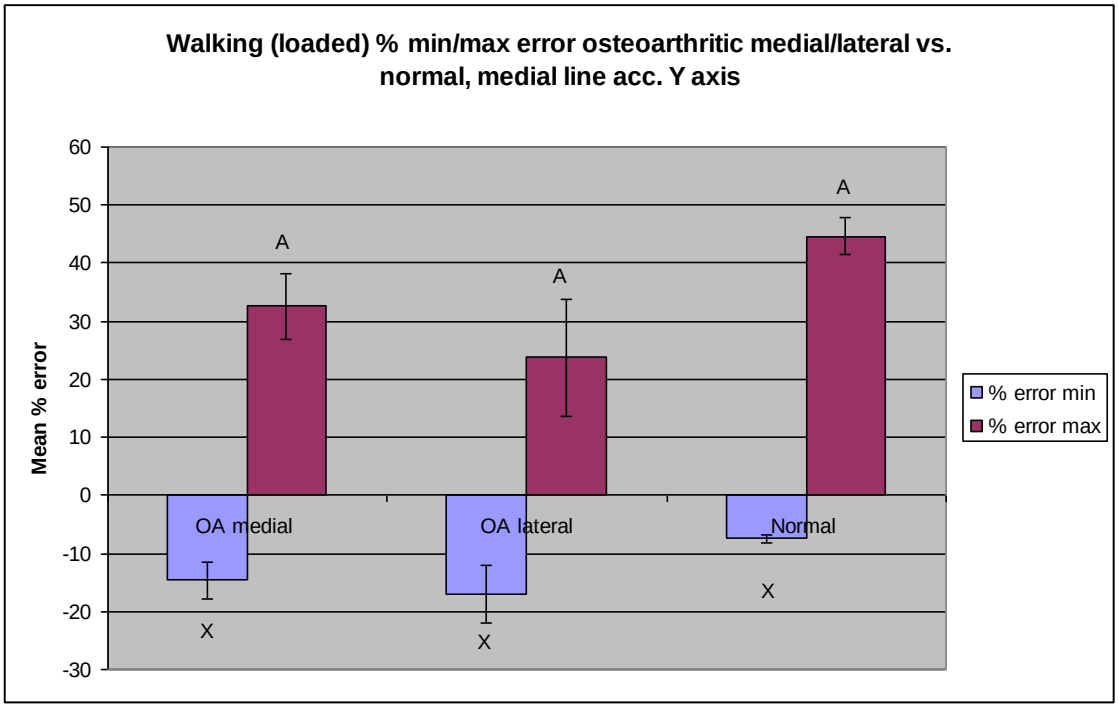


Figure 115. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

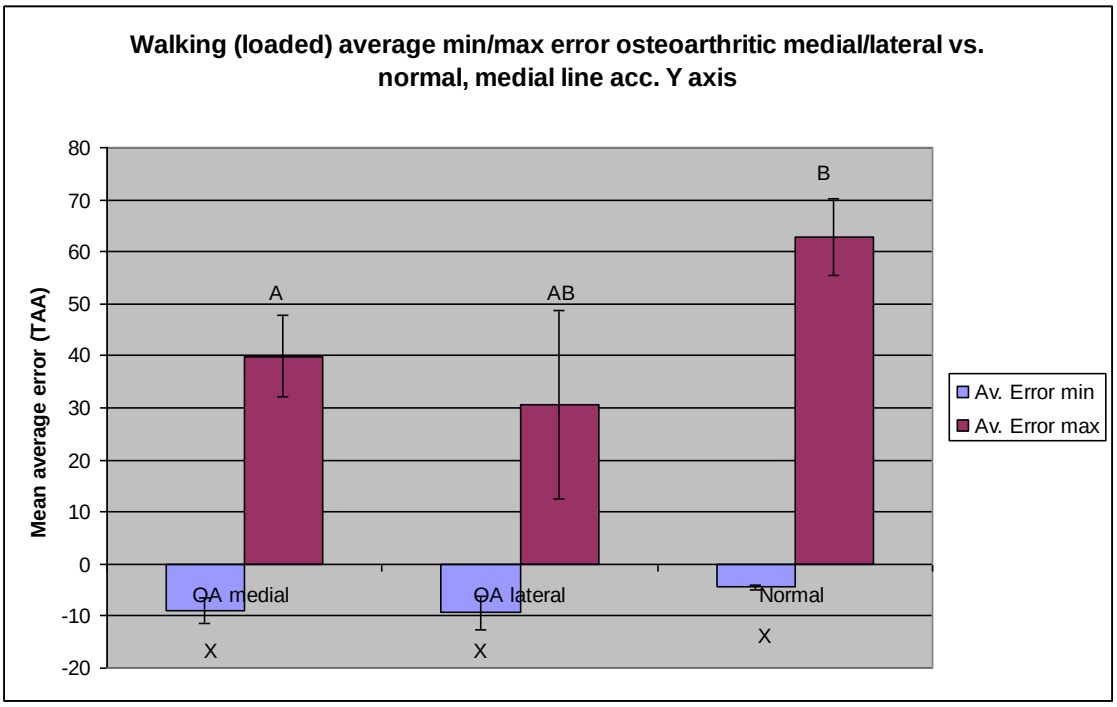


Figure 116. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

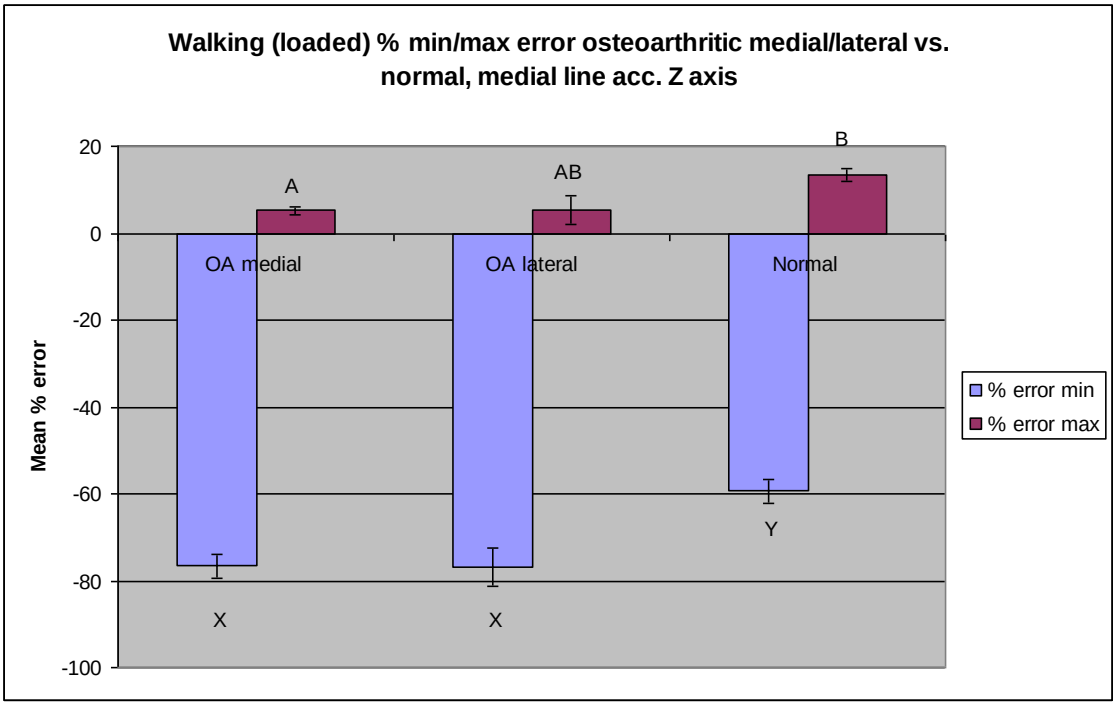


Figure 117. Mean values for walking (loaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

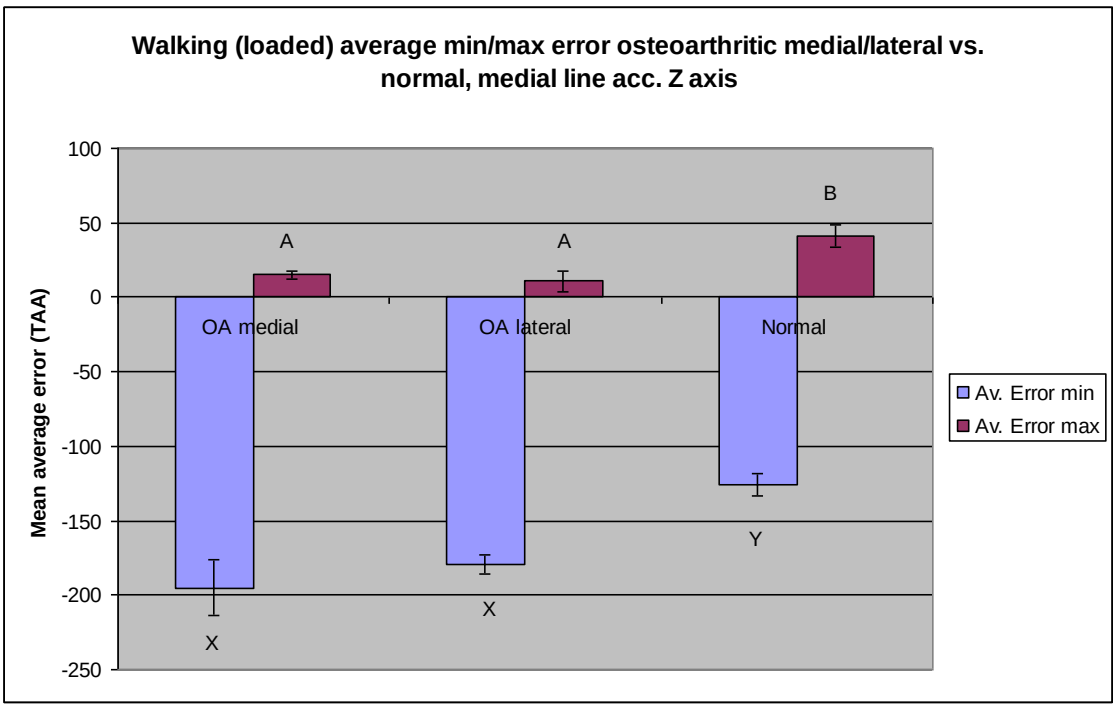


Figure 118. Mean values for walking (loaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 113-118 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the walking (loaded) protocol.

The X axis medial group differed from the normal group significantly for both % and average error minimum and maximum. The Y axis showed difference only between the medial maximum average error and normal. The Z axis showed significant differences between both % and average error minimum for the medial/lateral groups and normal. Both medial and lateral where different from normal for the average error maximum values but only the medial group showed this difference for % error maximum.
No significant difference was seen between any medial groups' values when compared with the lateral group.

5.33: Sitting/rising (loaded), medial and lateral osteoarthritic versus normal.

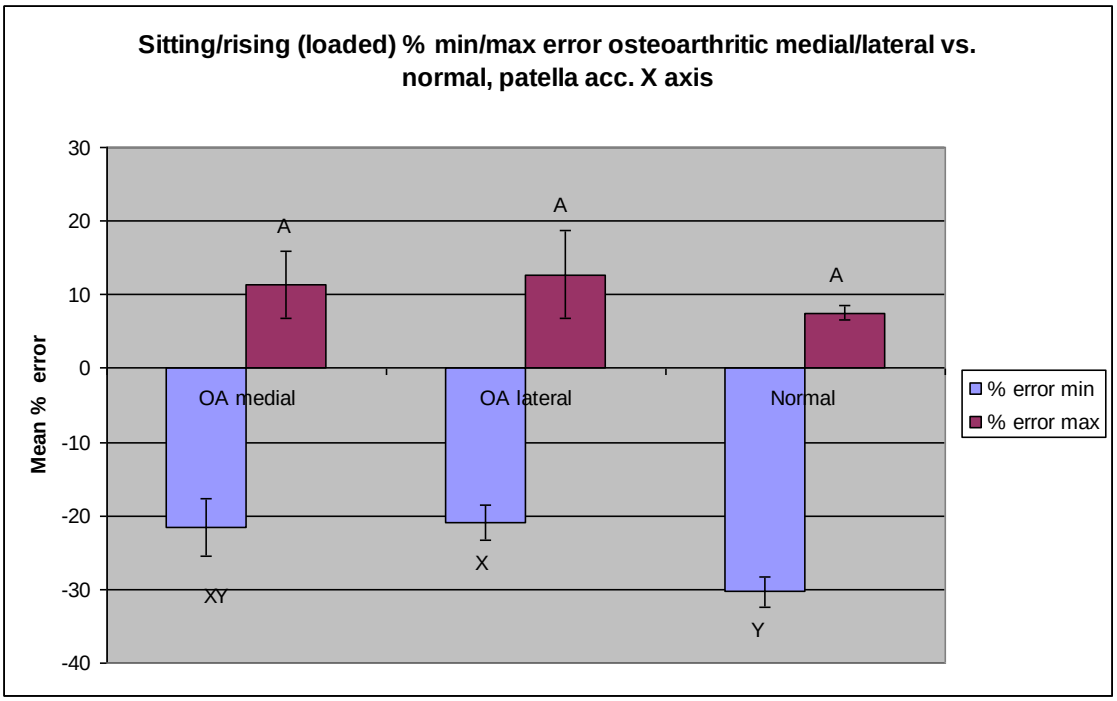


Figure 119. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

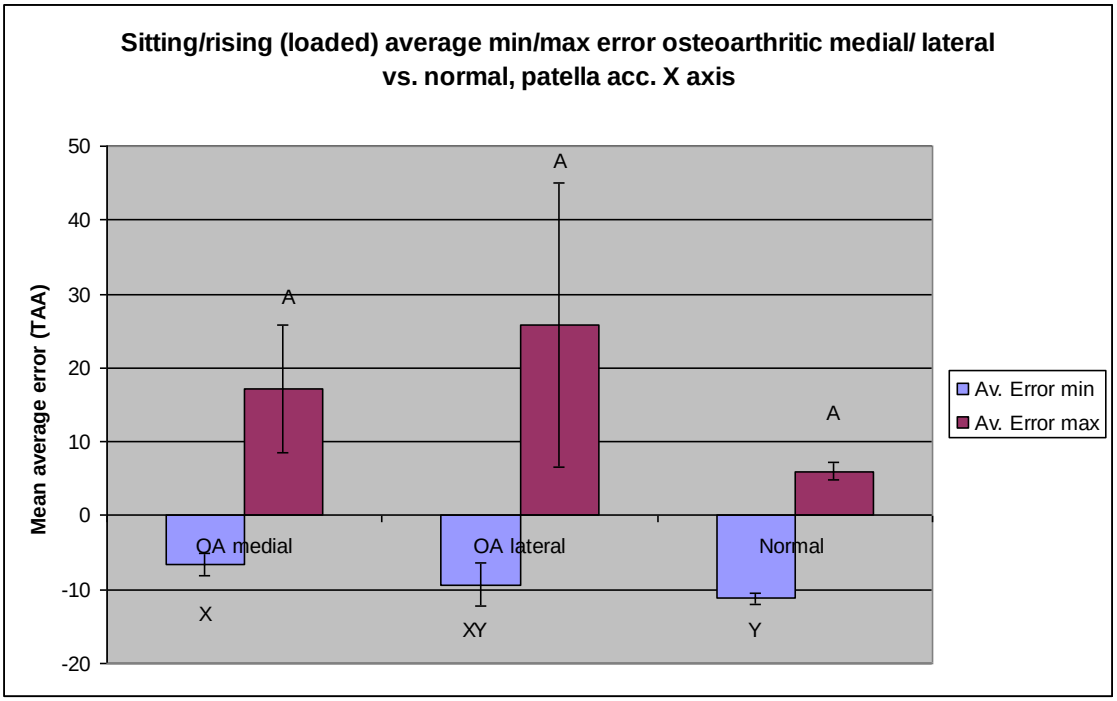


Figure 120. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, X axis of the patella accelerometer.

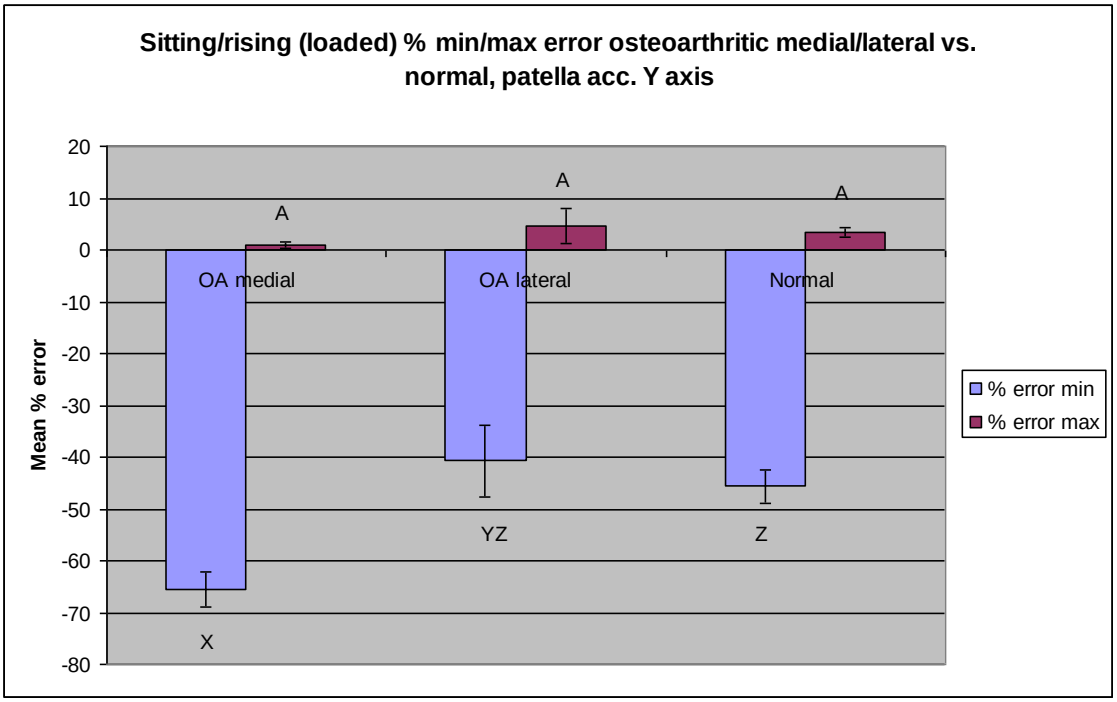


Figure 121. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

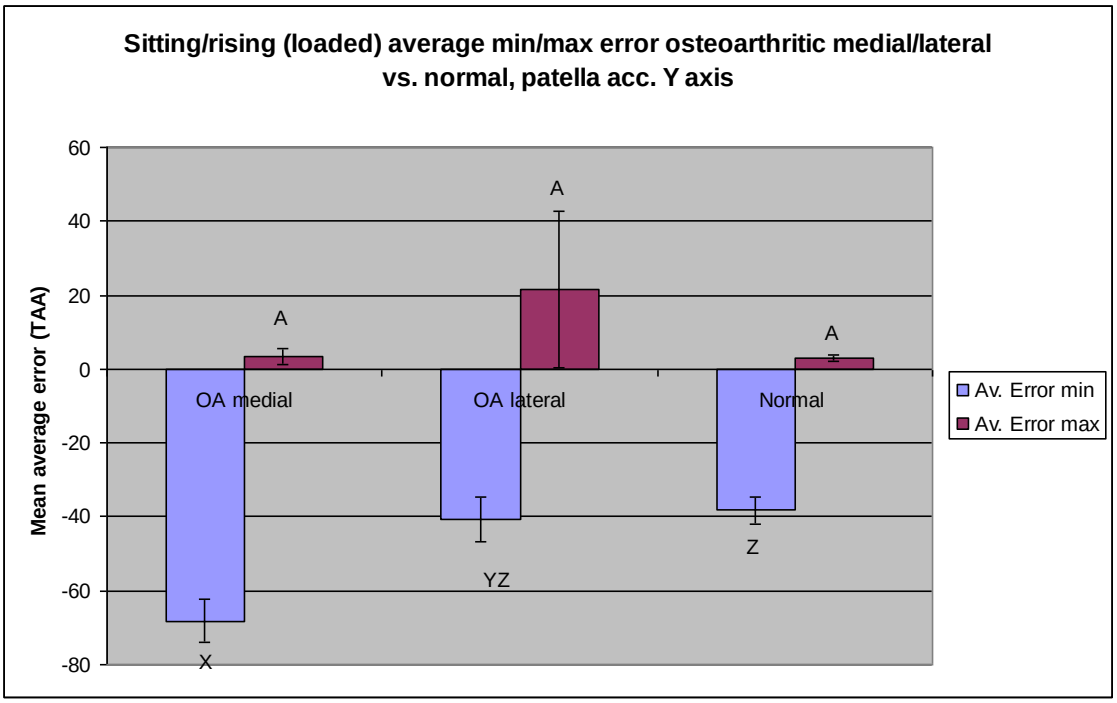


Figure 122. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the patella accelerometer.

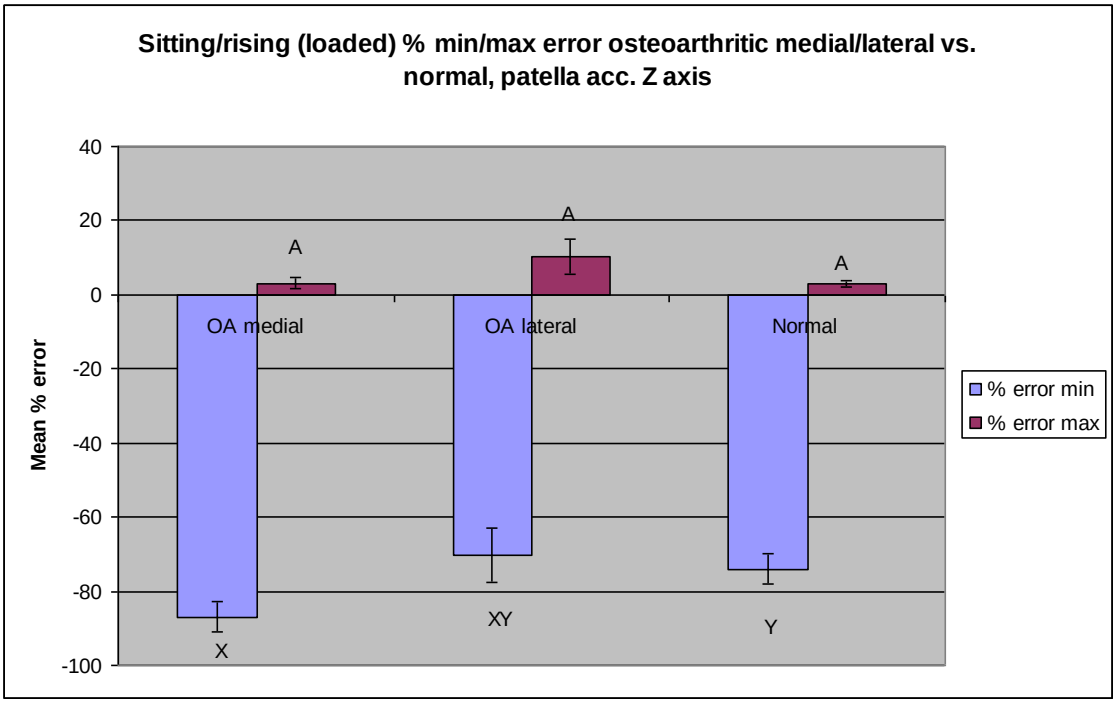


Figure 123. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

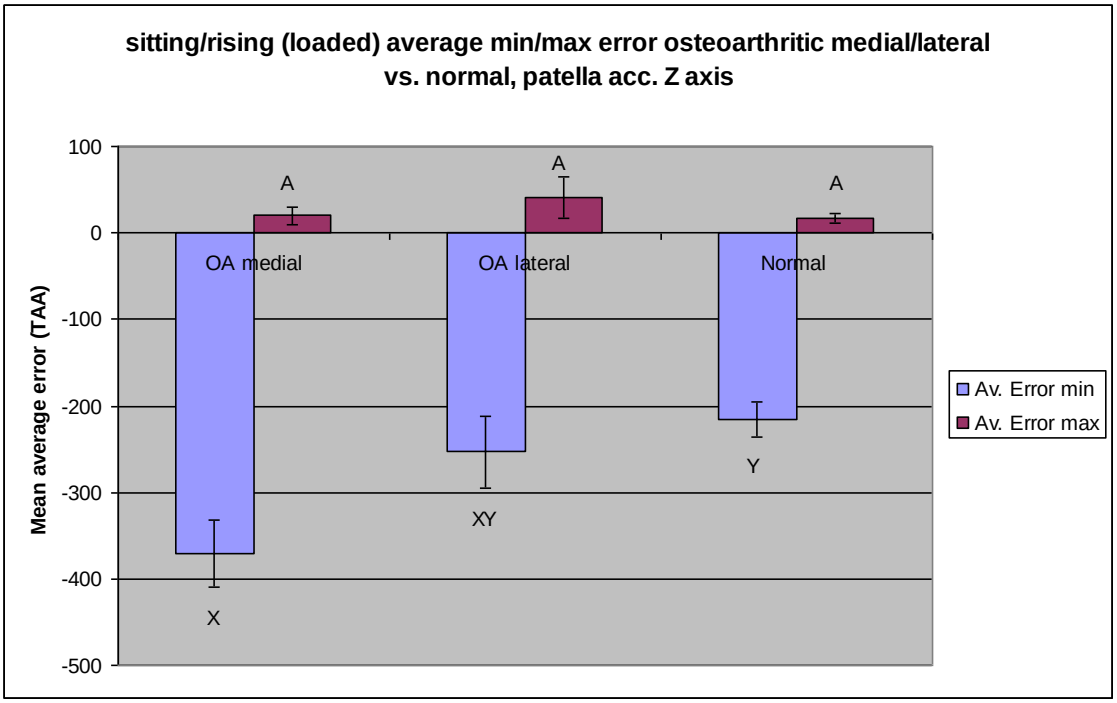


Figure 124. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the patella accelerometer.

The preceding figures 119-124 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the sitting/rising (loaded) protocol.

The X axis shows a significant difference between the % error minimum for the lateral and normal group and for the medial average error minimum and normal.
The Y axis shows significant differences for % and average error minimum for the medial group compared to the normal. It also shows a significant difference for % and average error minimum between the medial and lateral groups.

The Z axis show significant differences between the medial and normal groups for both % and average error minimum.

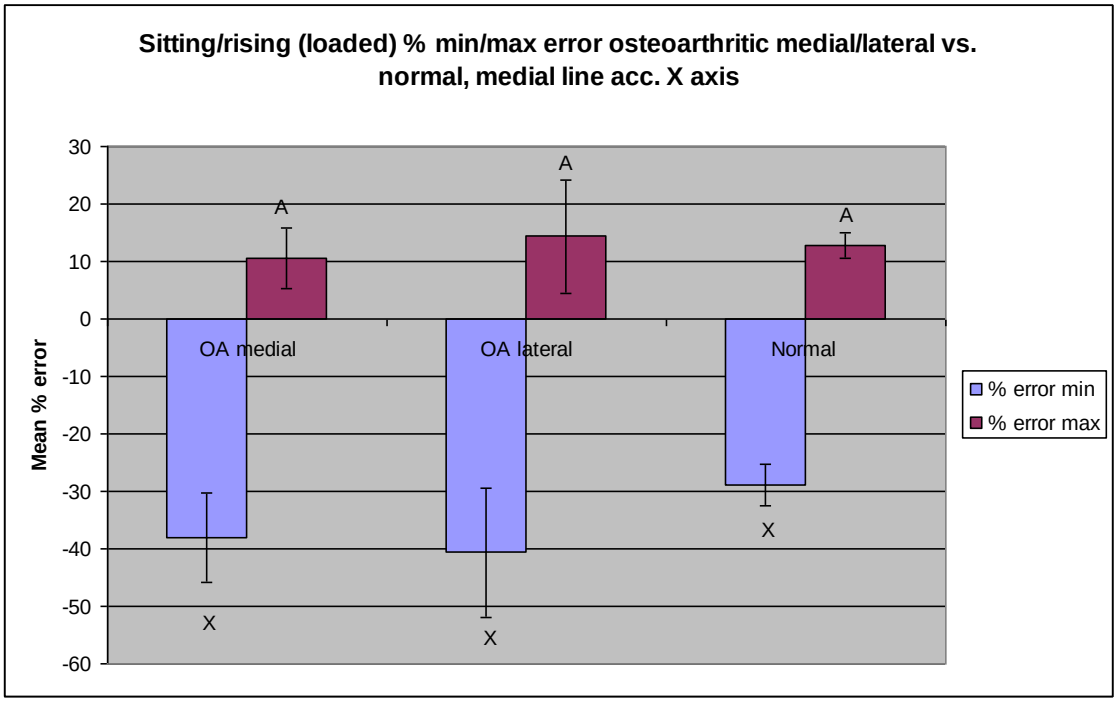


Figure 125. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

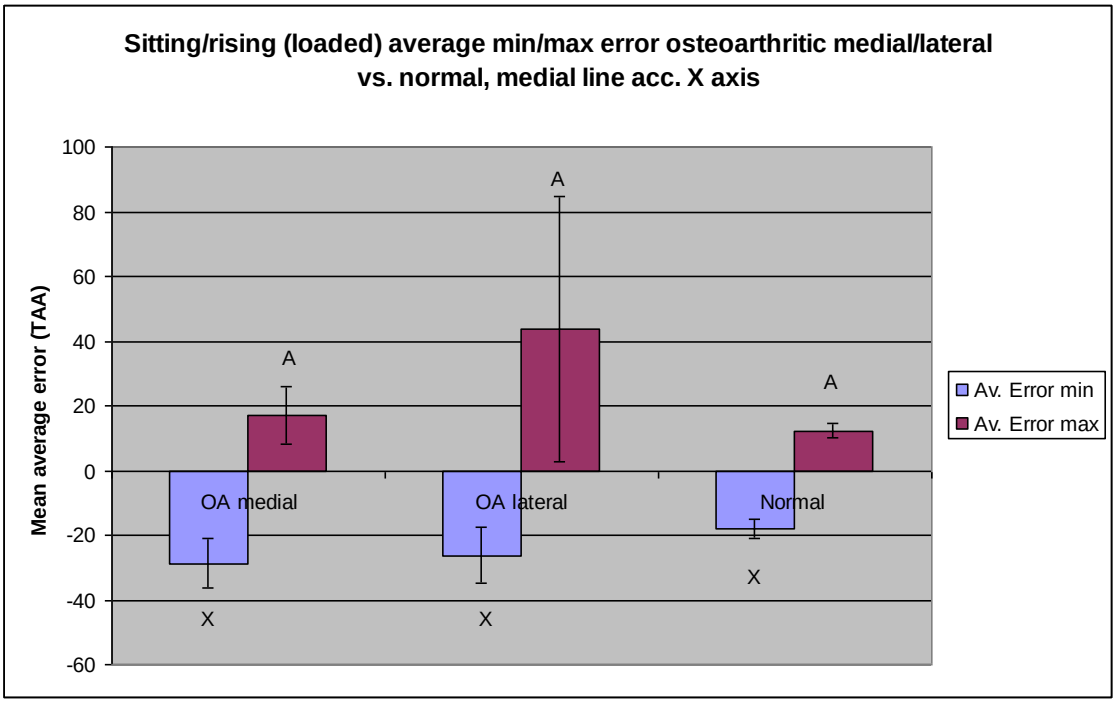


Figure 126. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, X axis of the medial line accelerometer.

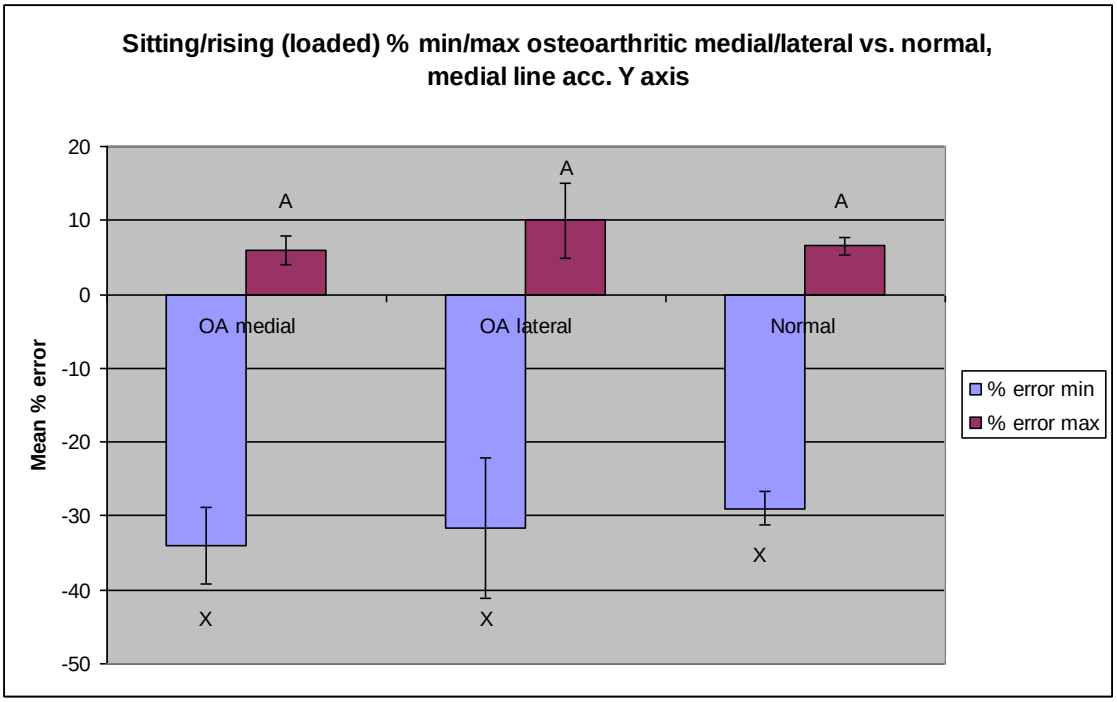


Figure 127. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

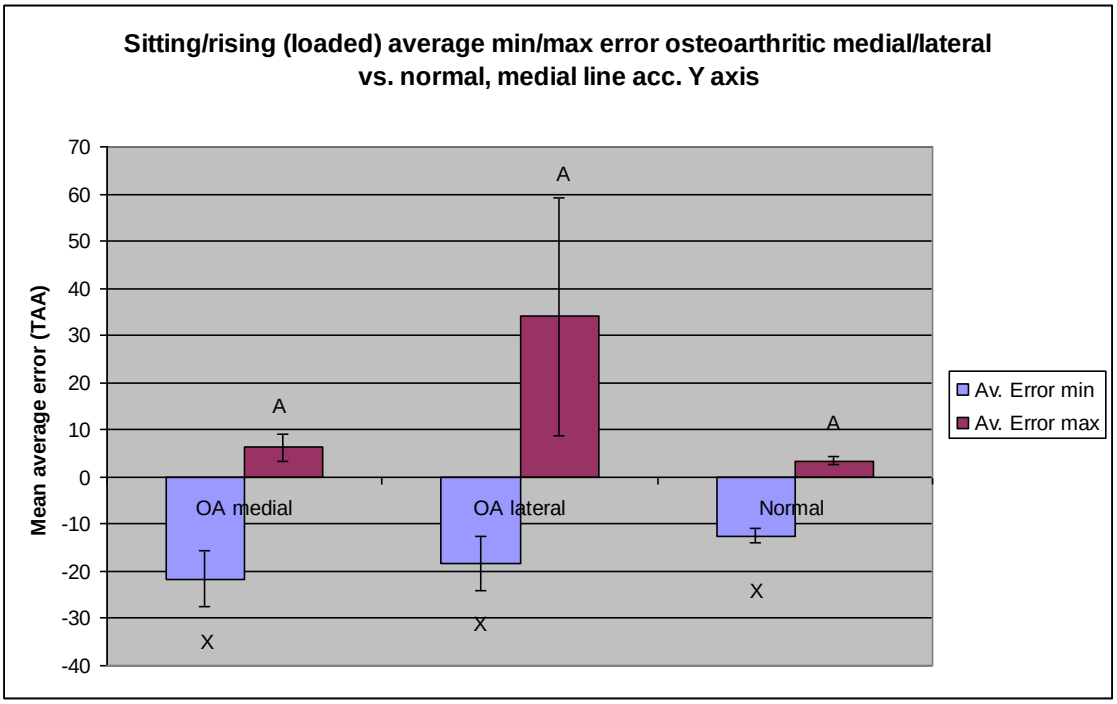


Figure 128. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, Y axis of the medial line accelerometer.

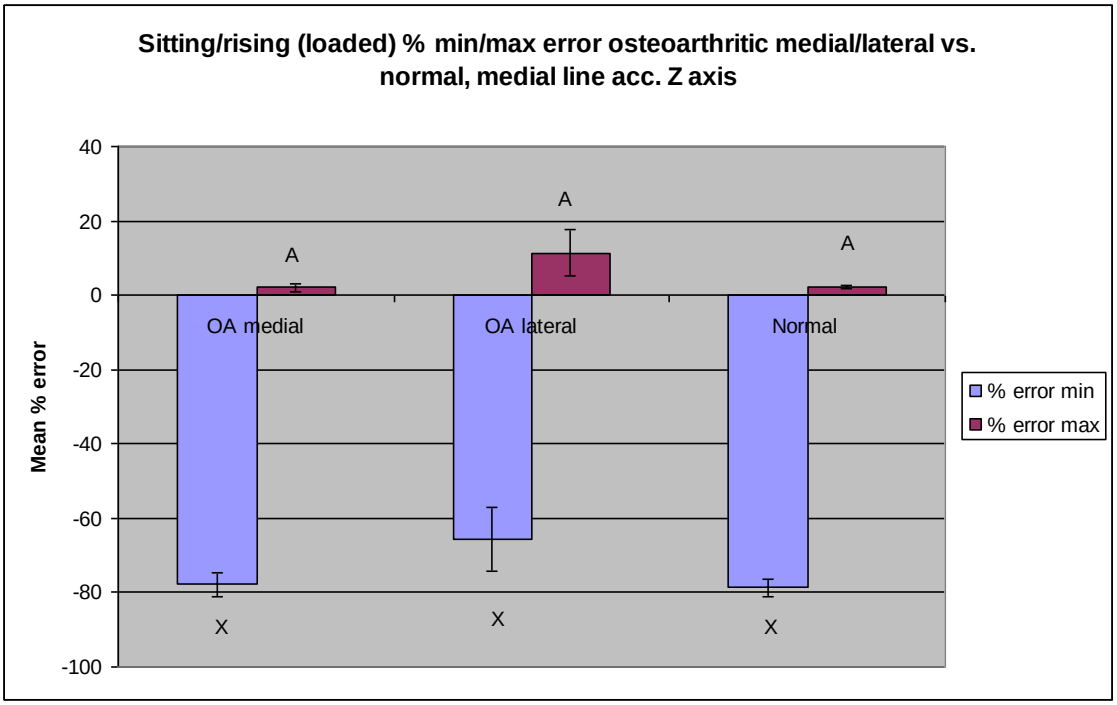


Figure 129. Mean values for sitting/rising (loaded) % min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

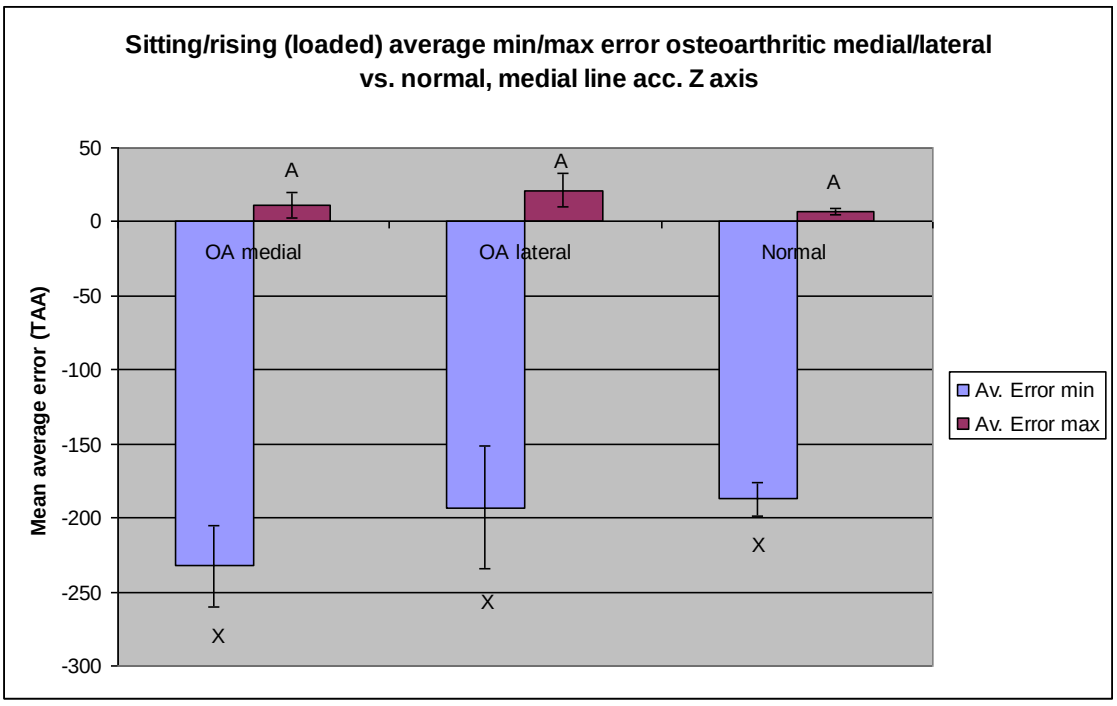


Figure 130. Mean values for sitting/rising (loaded) average min/max error, OA medial/lateral vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 125-130 show mean values for % error and average error for the medial and lateral compartment osteoarthritic affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the sitting/rising (loaded) protocol.

No significant differences were found between all comparisons across all axes on the medial line accelerometer

5.34: Discussion.

The first observation of note from the results for medial/lateral osteoarthritic versus normal group is that the levels of significant results are greatly reduced in this section. Where significant results are found they are found in comparisons between the two osteoarthritic subsets and the normal group, and these follow the pattern of suppression seen in the earlier section. Only one result showed a significant difference between lateral osteoarthritis and medial osteoarthritis.

There is some level of observable difference in actual values between the medial and lateral side of the knee joint that could be interpreted as relating to the location of the osteoarthritic damage within the knee but with out statistical significance it can only be concluded at this time that the phonoarthrometer cannot differentiate between medial and lateral osteoarthritic lesions in the knee.

Of note is the high standard error values found in some data groupings, a result of the lowered sample size caused by selection of the medial and lateral groups from the main osteoarthritic dataset. Undoubtedly these could be the cause of the lack of significance found in the given results.

Ideally, the phonoarthrometer if it is ever to be fully utilised as a diagnostic tool should be able to detect recordable differences between the medial and lateral side of the joint. Such detectable differences would be accounted for by differences in the transmission pathways from each compartment to the respective accelerometer.

As a possible theory to explain these differences in the transmission pathway can be related to the shape and size of the menisci. The lateral meniscus covers proportionally more of the tibial plateau than the medial meniscus (Mascarenhas, Dillon and MacDonald, 2012) and its shape is almost a complete circle as opposed to the medial meniscus which is very much a semi circular crescent this is to allow the attachment points for the various ligaments most notably the ACL/PCL.

The body's weight is transmitted down through the femur and is distributed evenly in a healthy knee joint between the medial and lateral compartments (Johnson et al., 1980, Fox et al., 2012). This suggests that a greater proportion of the weight load would be transmitted through the greater surface area of the lateral meniscus, resulting in a more even distribution of the load through the knee joint. Figure 131 gives a diagrammatic view of this; note surface area percentages are simplified estimates for illustrative purposes.

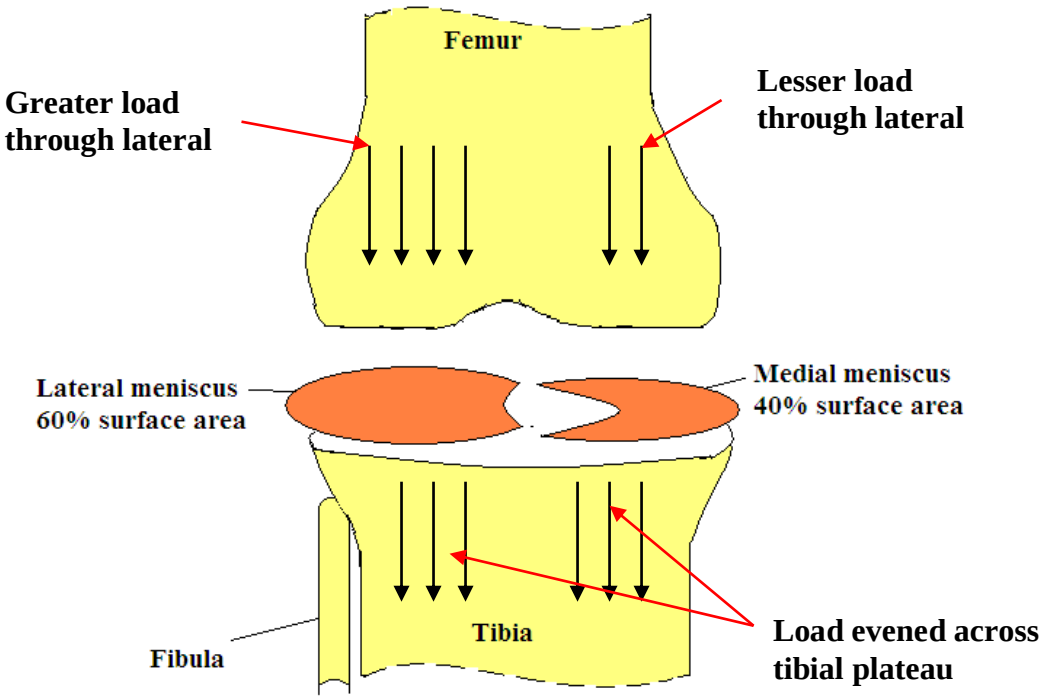


Figure 131. Distribution of load across the knee joint

If detectable differences from the lateral and the medial compartments of OA affected joint could be detected by a more focussed version of the phonoarthrometer, it would suggest that this even spread of weight distribution changes dramatically in the presence of OA in the joint. Wearing away of either the medial or lateral menisci causes a corresponding increase in pressure in that compartment and a decrease in the other compartment. Due to the differences in the shape and surface area of the menisci, this pressure that results from the osteoarthritis in the joint will not be even between the two

compartments and hence differing vibration responses are observed for the medial and lateral osteoarthritic joint vibration responses.

5.4: Comparison of severity of osteoarthritic lesion data with normal knee joint group data.

The following section presents the data as a series of graphs showing the mean values of % min/max error and average min/max error for osteoarthritic knee joint groups divided based on the severity of the lesion within the knee and the normal knee joint group. The severity of the osteoarthritis was identified from within the main osteoarthritic group by the use of the surgeon's notes and a diagnosis based on the Kellegren-Lawrence scale. As for the main results the data is divided according to the protocol type performed (swing (unloaded), walking (loaded) and sitting/rising (loaded)) and according to the accelerometer position (patella or medial line) used to collect the vibration signal. Positive values denote % and average error maximum values, negative values denote % and average error minimum values in each case, in effect these represent the level of deviation for each group above (maximum) or below (minimum) the prediction corridor as produced following analysis of the vibration signal by the phonoarthrometer software. The values were plotted negatively for the minimum data in order to graphically represent % and average error falling below the prediction corridor. For each plotted data point error bars are shown, representing the standard error of the sample means from the data set. T test comparisons of the sample means were carried out for each error min/max dataset, with the significance level set at $p<0.05$. Results of the comparisons are denoted by the letters above each data point; means with different letters are significant, this follows the method as described for the medial/lateral/normal comparisons.

5.41: Swing (unloaded), osteoarthritic grade 1-4 versus normal.

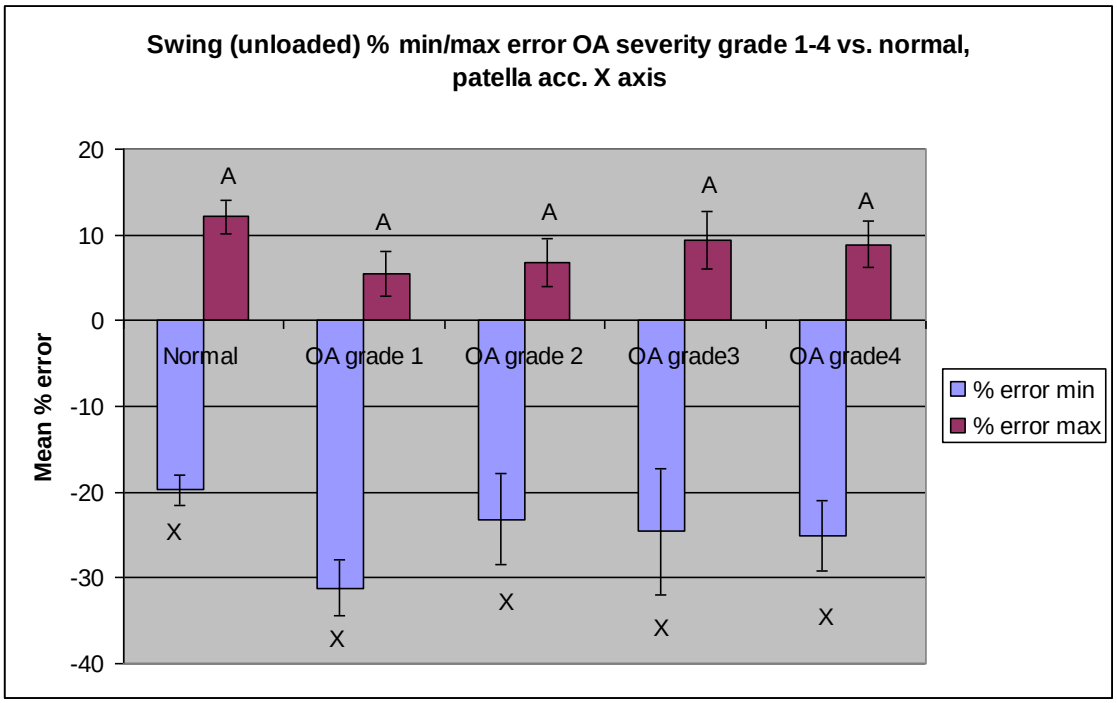


Figure 132. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

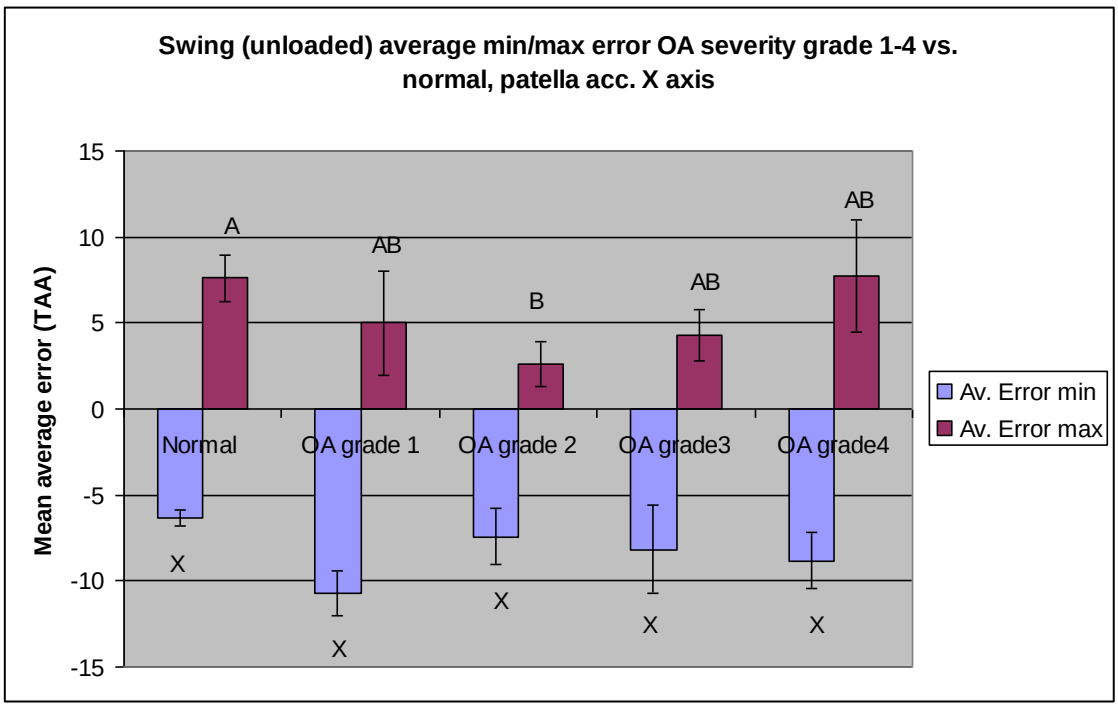


Figure 133. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

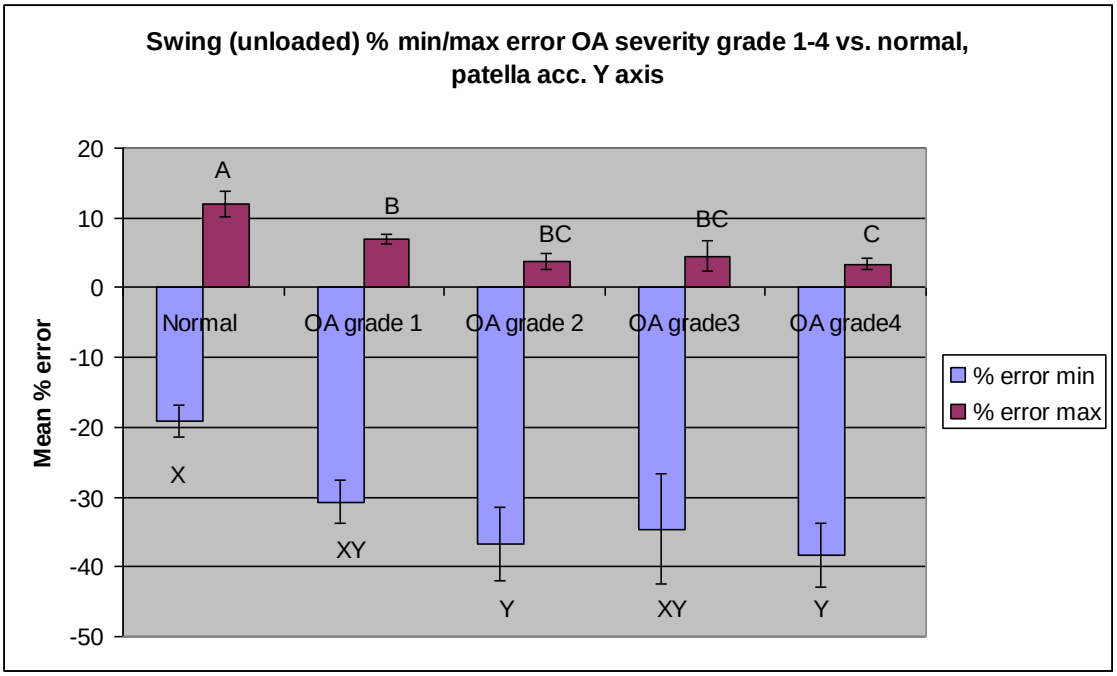


Figure 134. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

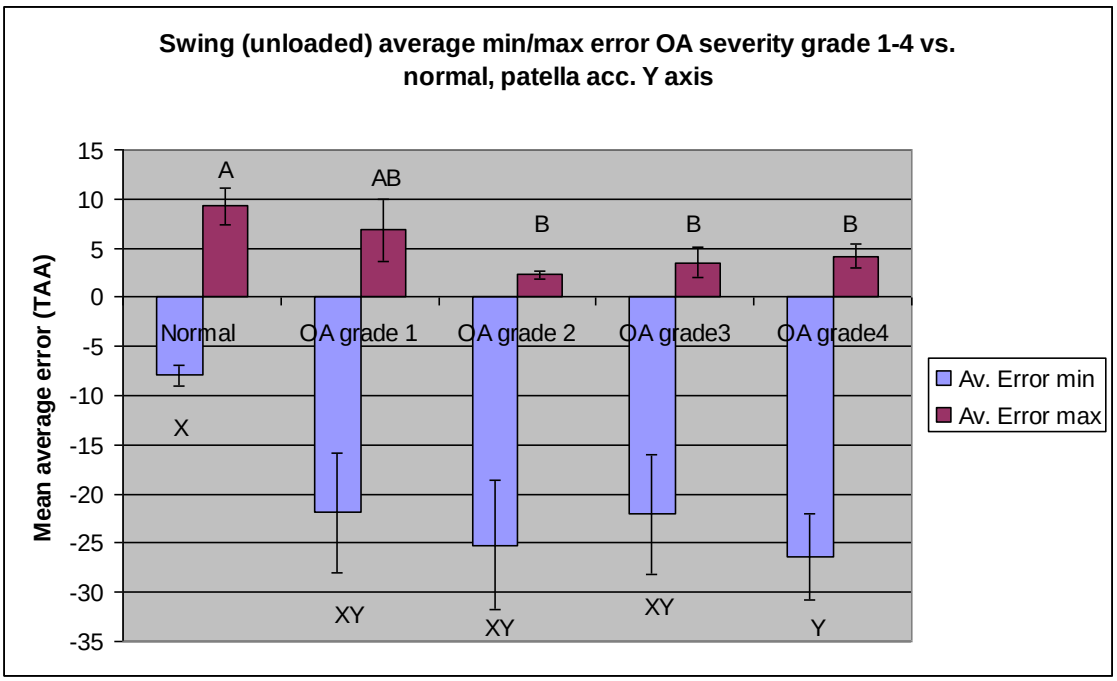


Figure 135. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

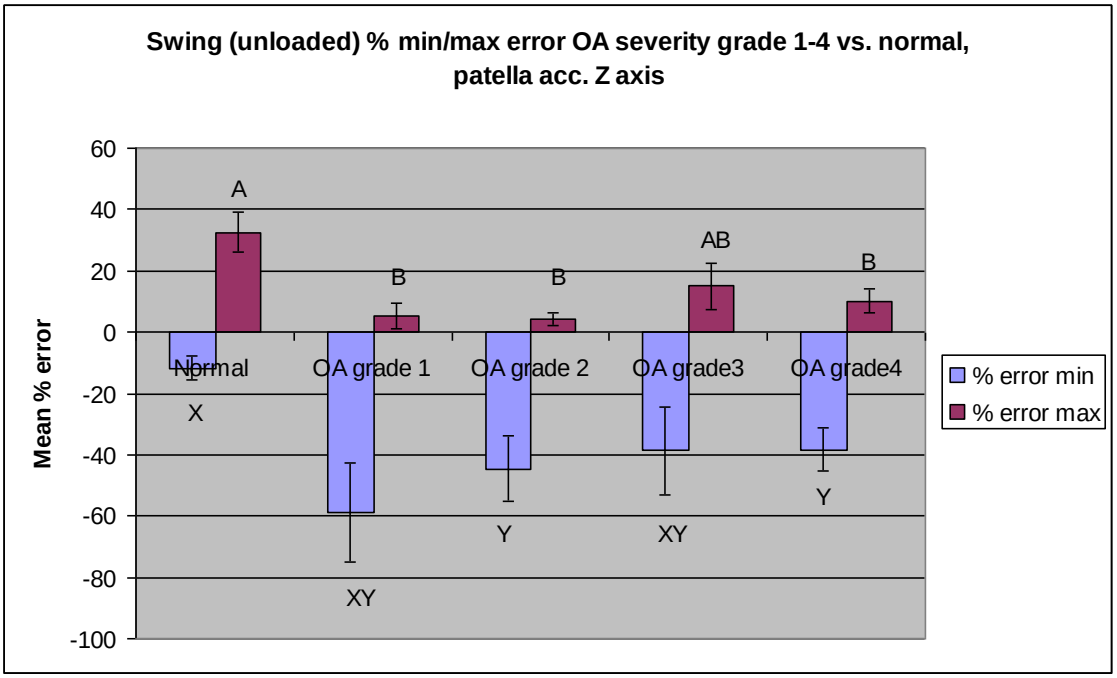


Figure 136. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

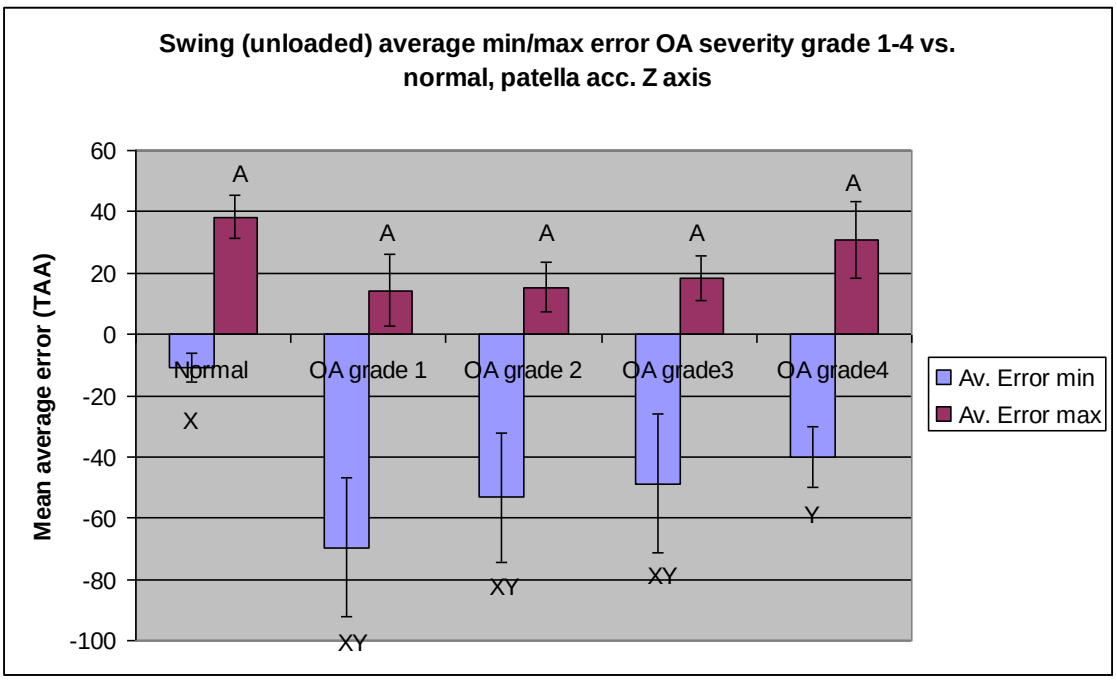


Figure 137. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

The preceding figures 132-137 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the swing (unloaded) protocol.

The X axis shows significance only in grade 2 osteoarthritis compared to normal for the average error maximum value.
The y axis % error maximum shows significantly differing values when all osteoarthritic grades are compared to normal, grade 1 also differs from grade 4.
% error minimum values show difference when both grade 2 and 4 are compared to normal. For average error maximum values differ when grade 2, 3 and 4 are compared to normal and average error minimum shows differences when grade 4 and normal are compared.
The Z axis shows differences between % error maximum values for grades1, 2 and 4 compared to normal, % error minimum values differ when grade 2 and 4 are compared with normal. Average error minimum values show differences when grade 4 is compared to normal and when grade 4 is compared to grade 1.

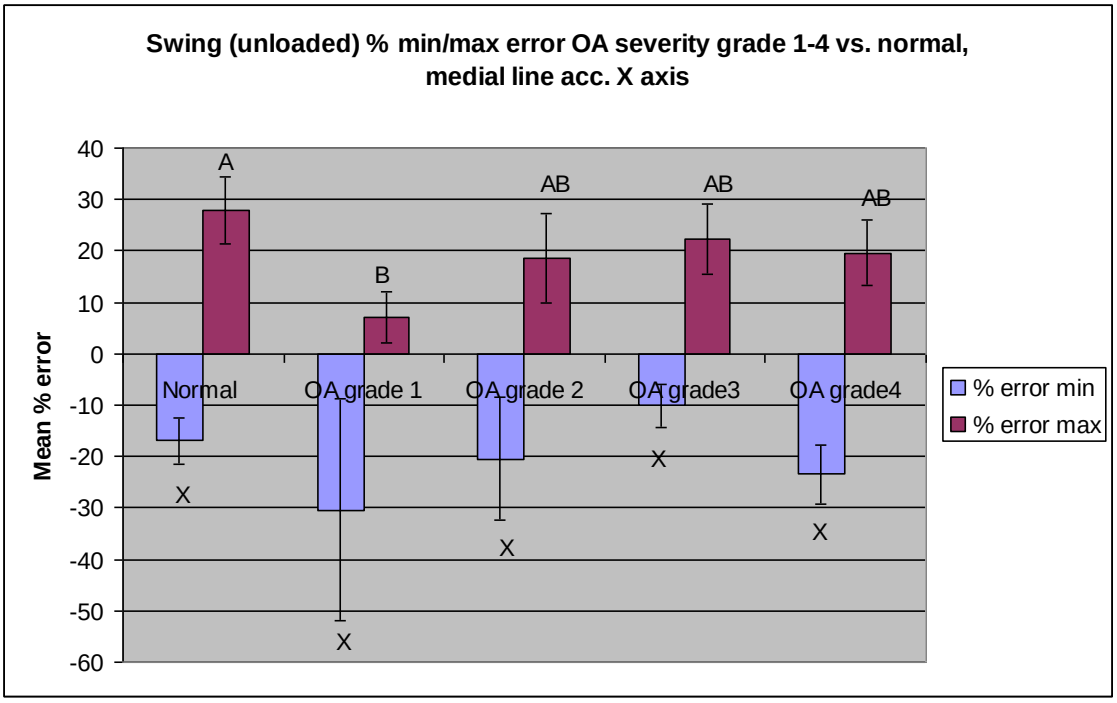


Figure 138. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

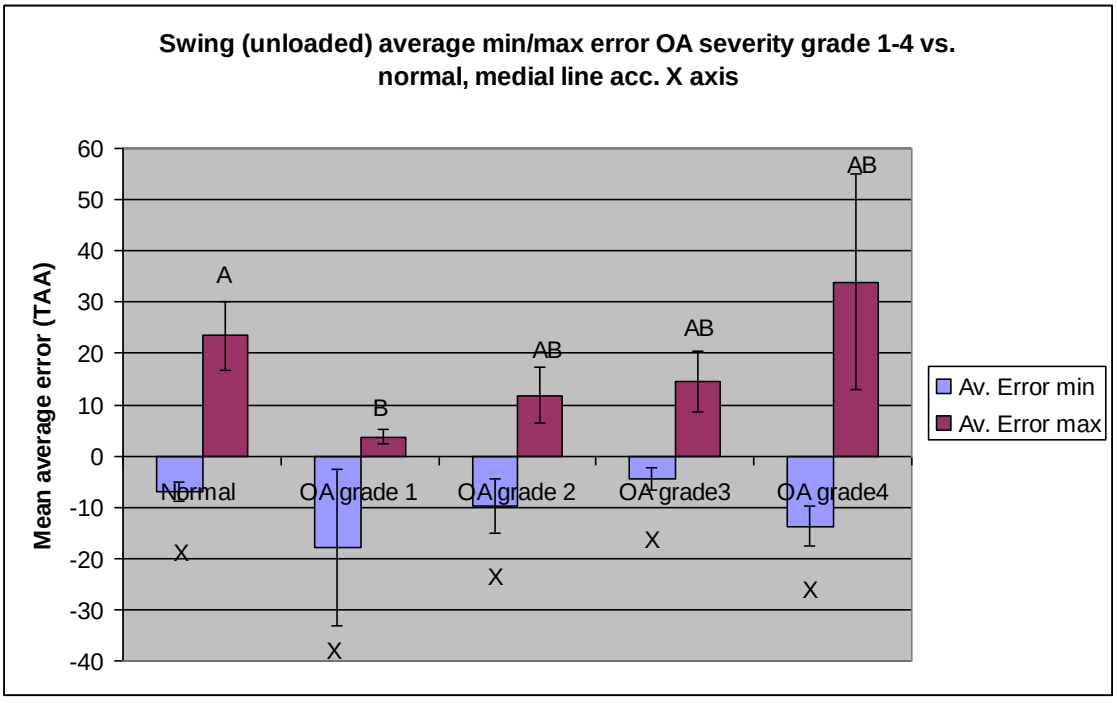


Figure 139. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

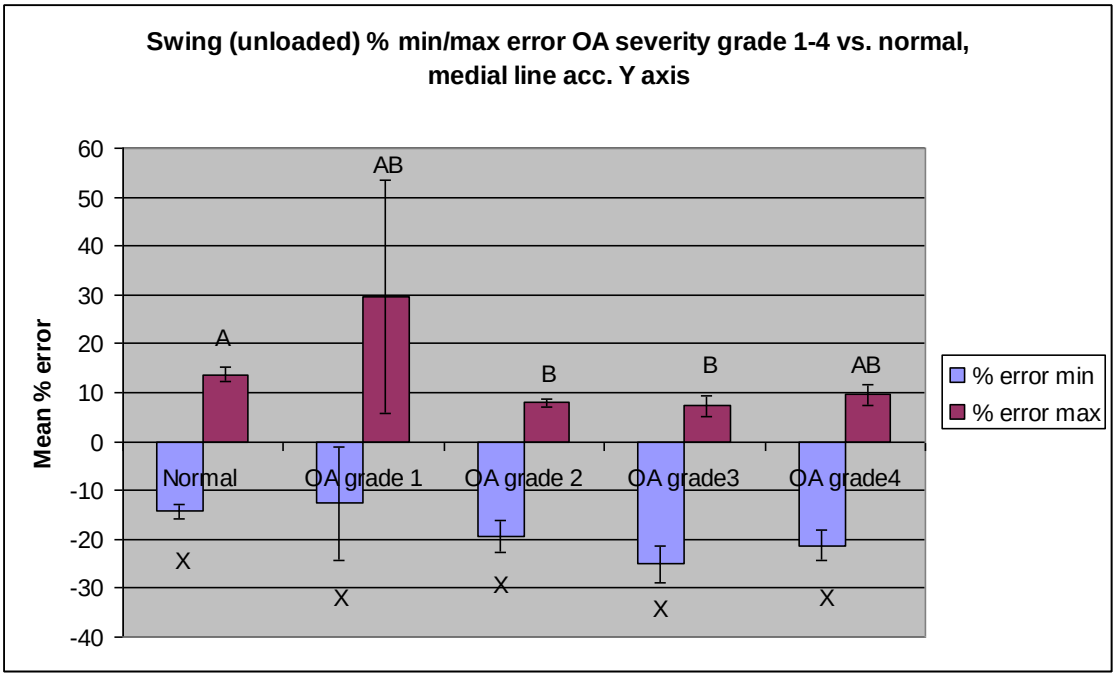


Figure 140. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

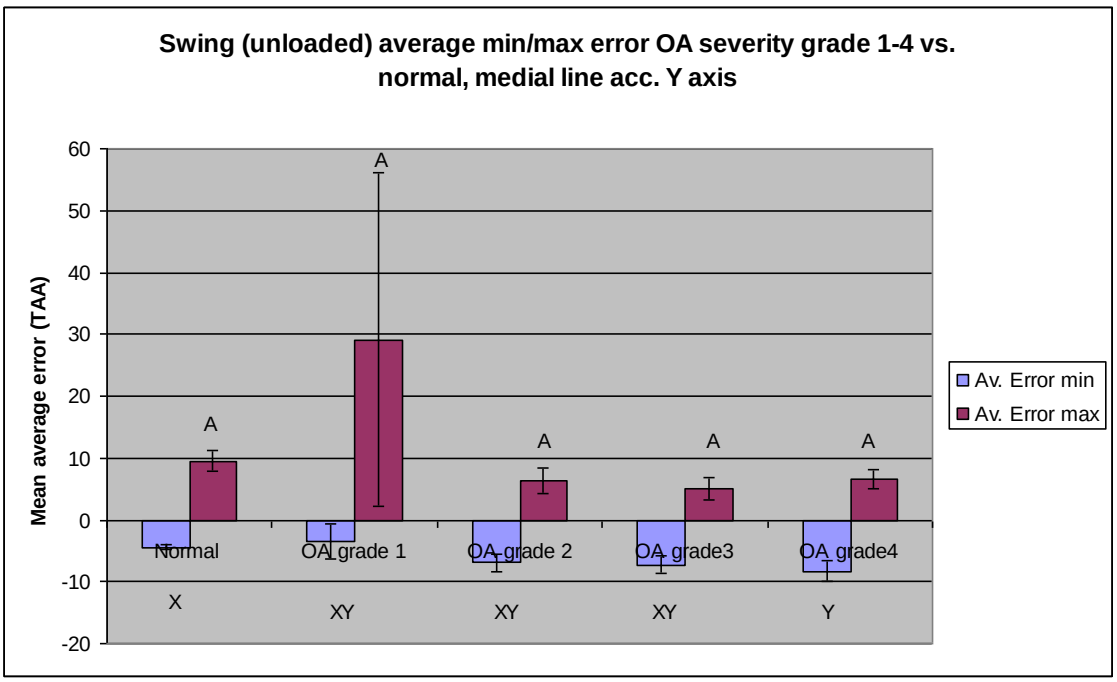


Figure 141. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

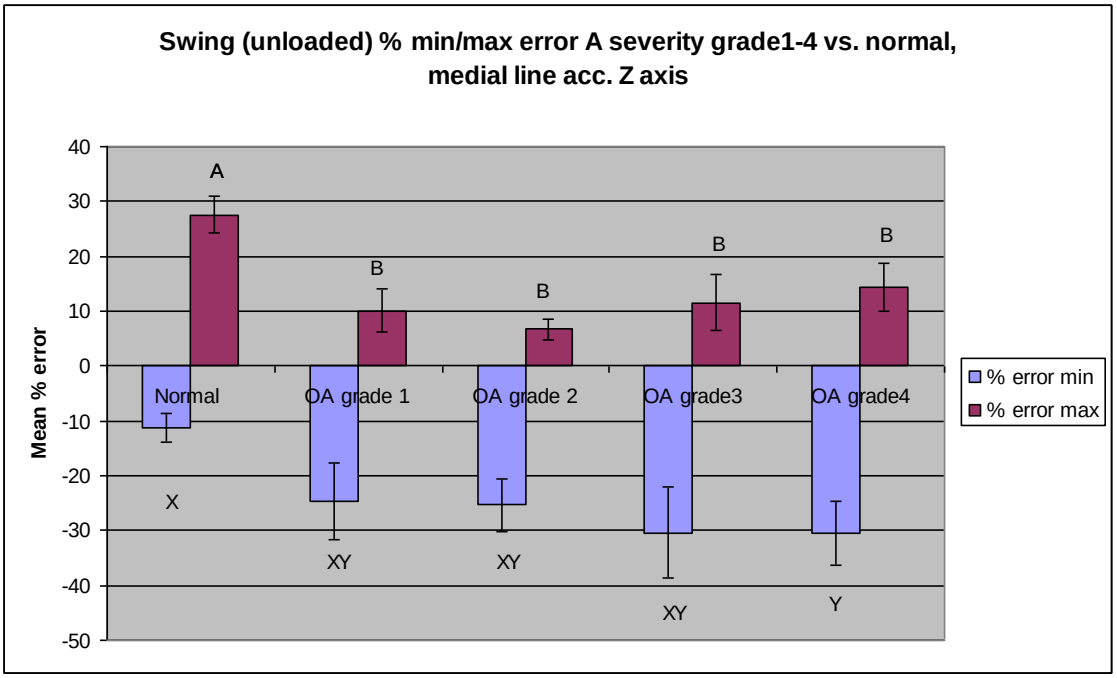


Figure 142. Mean values for swing (unloaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

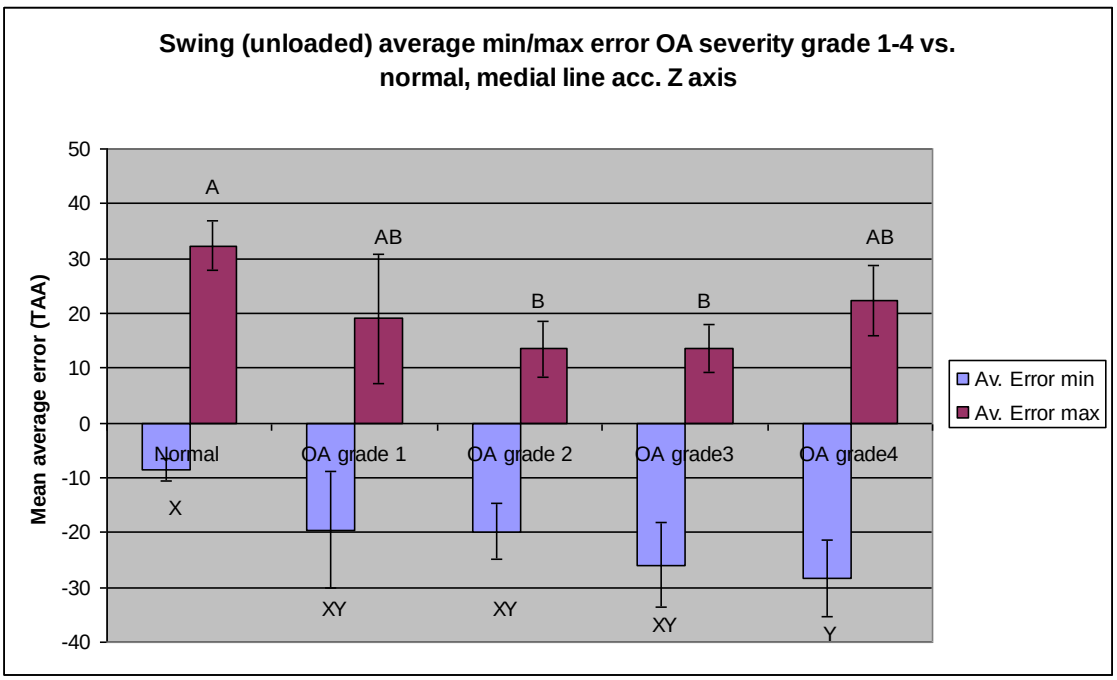


Figure 143. Mean values for swing (unloaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 138-143 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the swing (unloaded) protocol.

The x axis shows significant difference in the % error maximum values when normal and grade 1 are compared. Average error maximum values show significant difference when normal and grade 1 is compared.
The Y axis shows difference in the % error maximum values when normal compares with grade 2 and 3. Average error minimum shows difference when normal is compared to grade 4.
Z axis results show a significant difference between all osteoarthritic grades and normal for % error maximum, differences are seen between average error maximum values for grades 2 and 3 compared to normal and average error minimum values for grade 4 compared with normal.

5.42: Walking (loaded), osteoarthritic grade 1-4 versus normal.

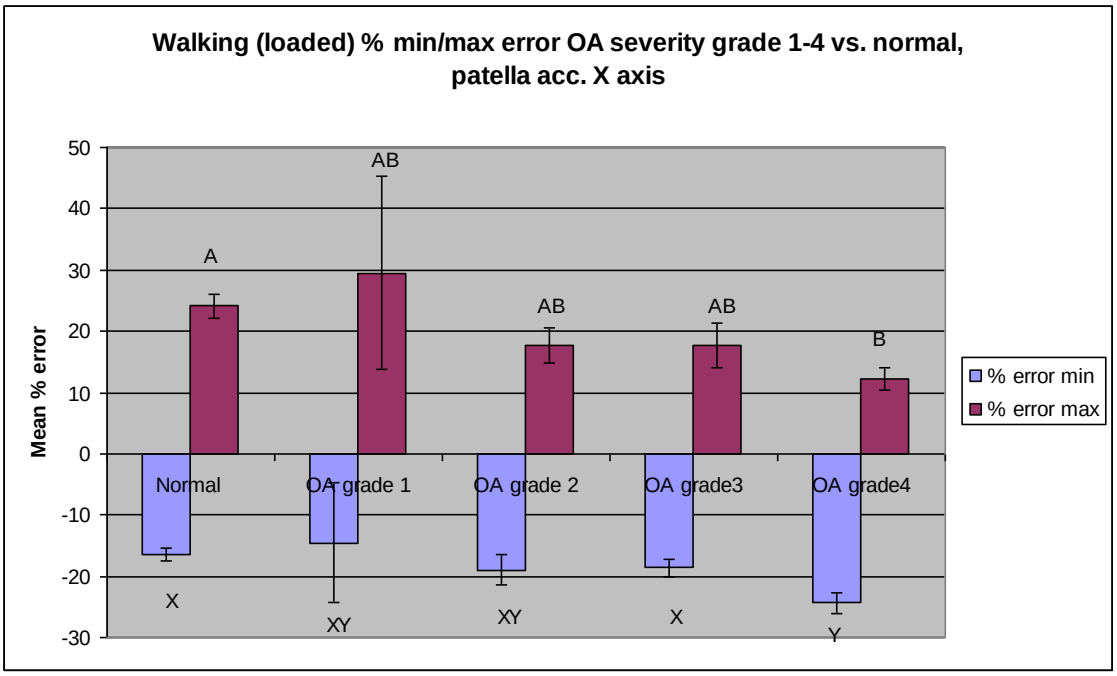


Figure 144. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

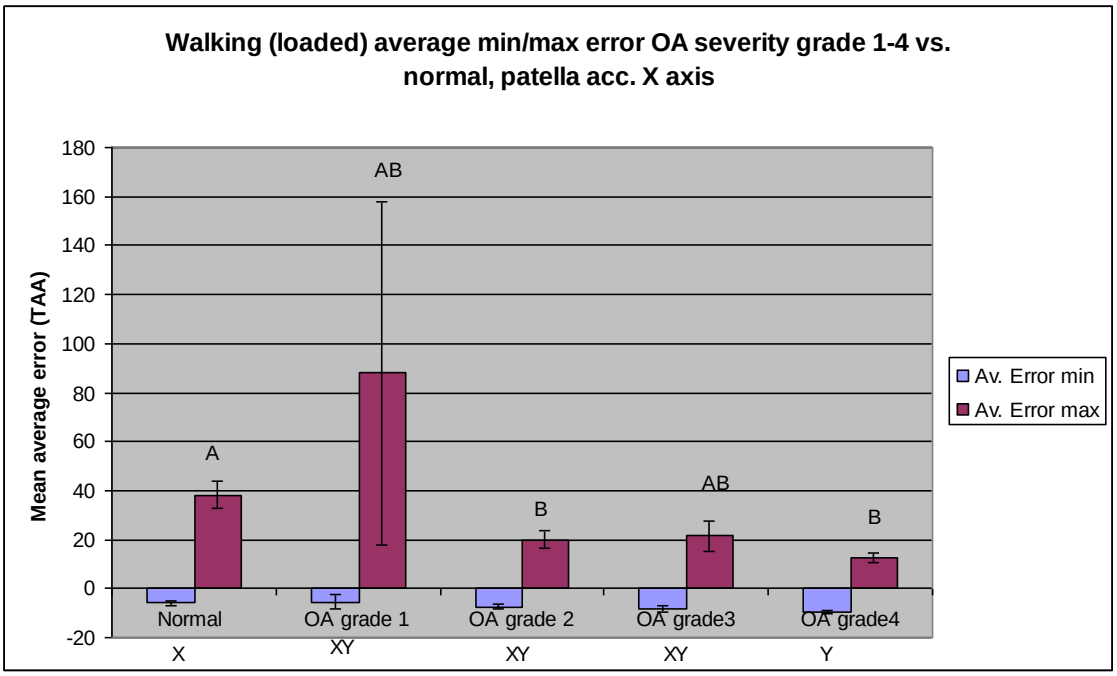


Figure 145. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

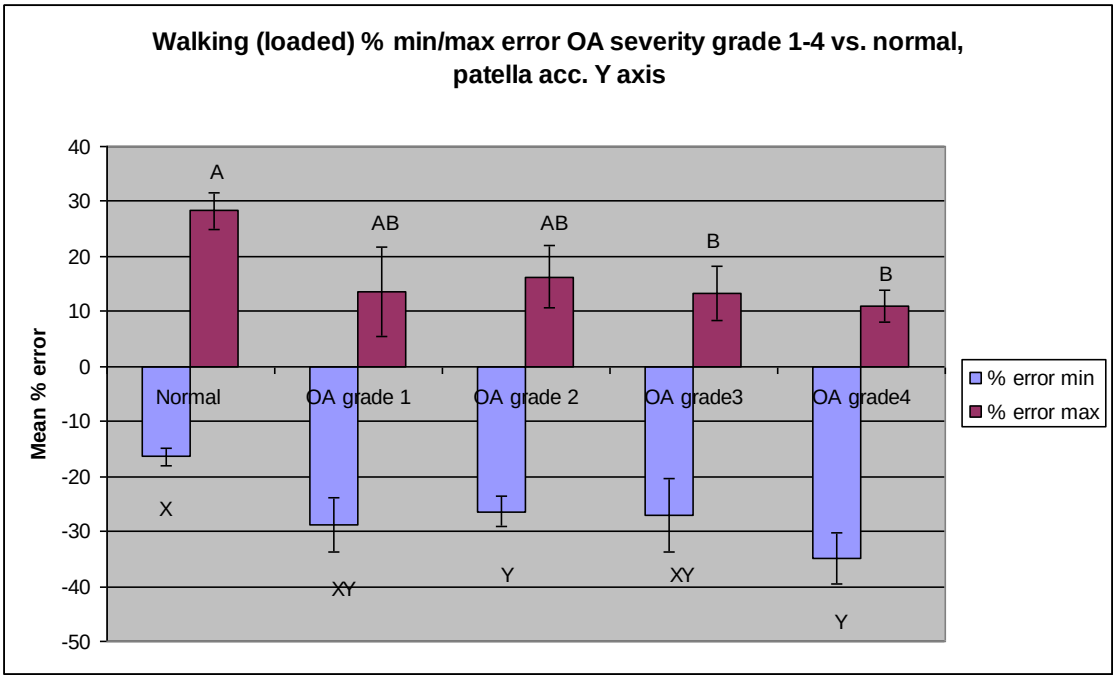


Figure 146. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

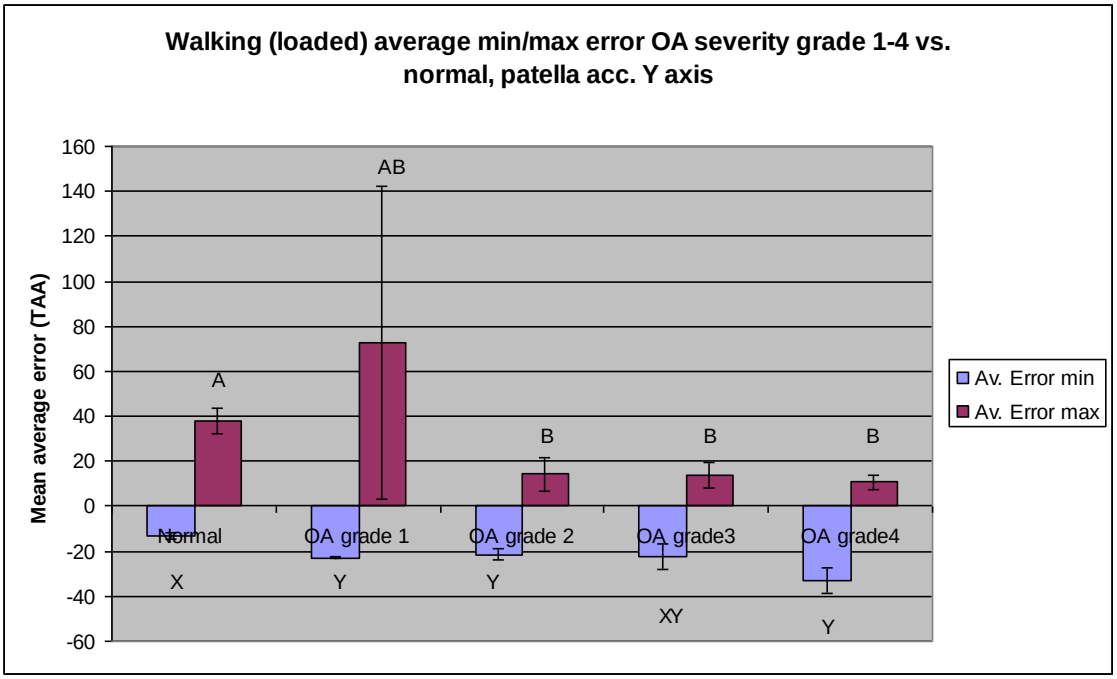


Figure 147. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

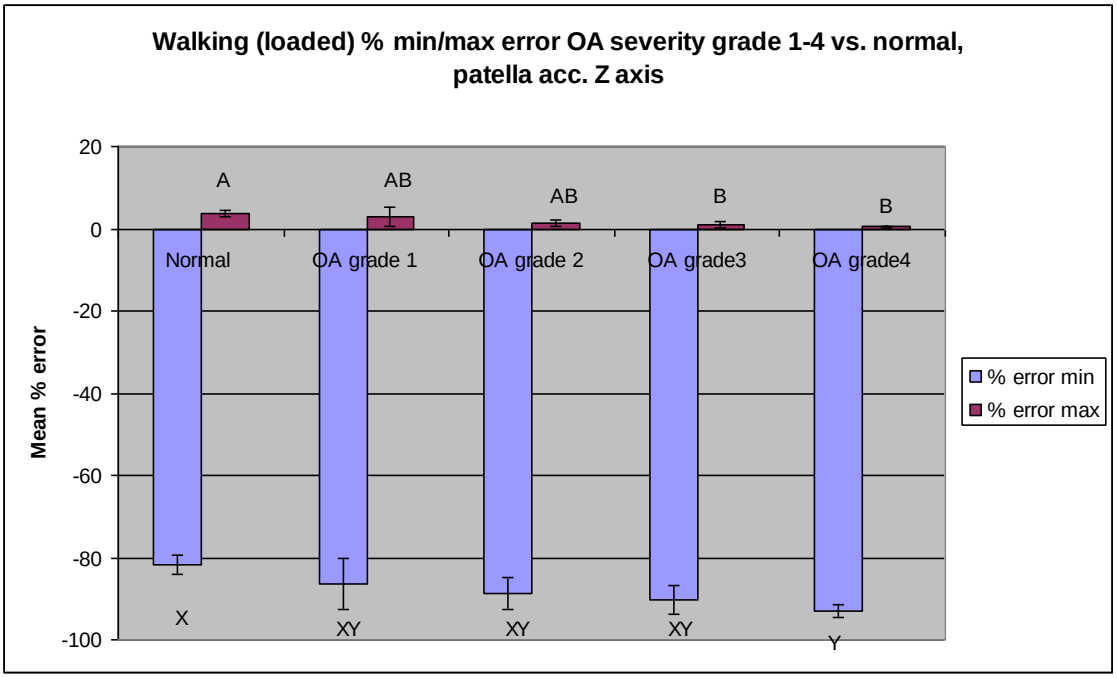


Figure 148. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

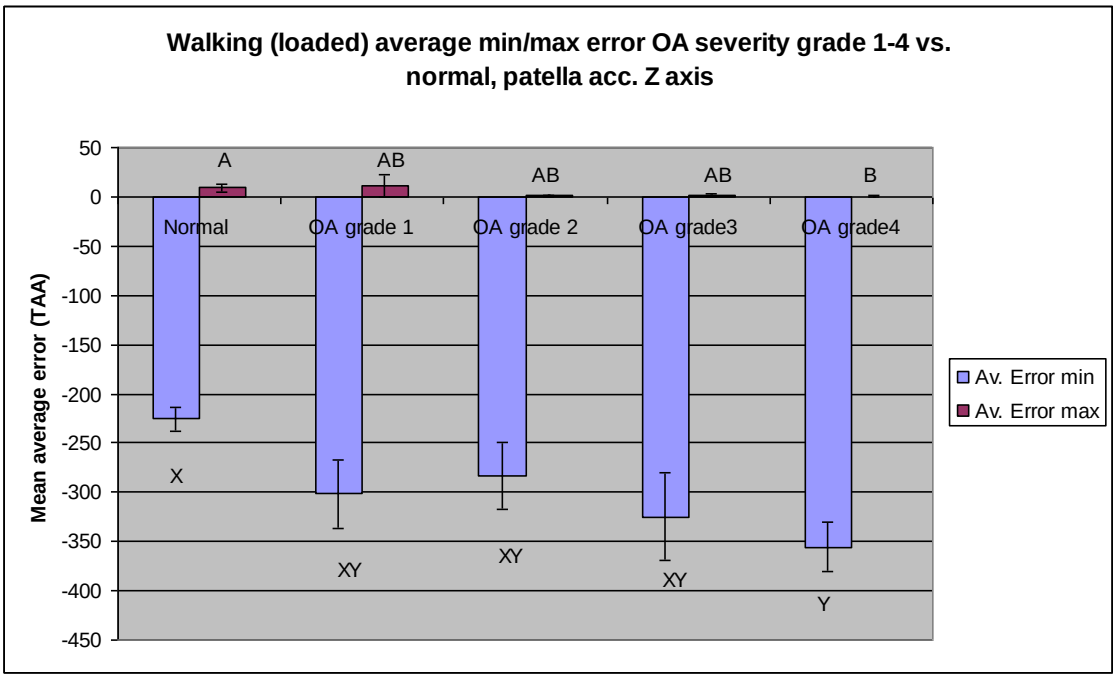


Figure 149. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

The preceding figures 144-149 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the walking (loaded) protocol.

The X axis show differences when % maximum error values for grade 2 and 4 are compared to normal. % minimum error values show significant differences between grade 4 and normal and between grade 3 and grade 4. Average error maximum values differ when normal is compared to grades 2, 3 and 4; average error minimum values differ when grade 4 and normal are compared.

The Y axis shows differences in % maximum error when grade 3 and 4 are compared to normal, and differences in % minimum error values when grade 2 and 4 are compared to normal.

Average error maximum values differ when grades 2, 3 and 4 are compared with normal, average error minimum values differ when grade 1, 2 and 4 are compared to normal.

Z axis results show significant differences between grades 4 and normal for % and average error maximum and minimum values.

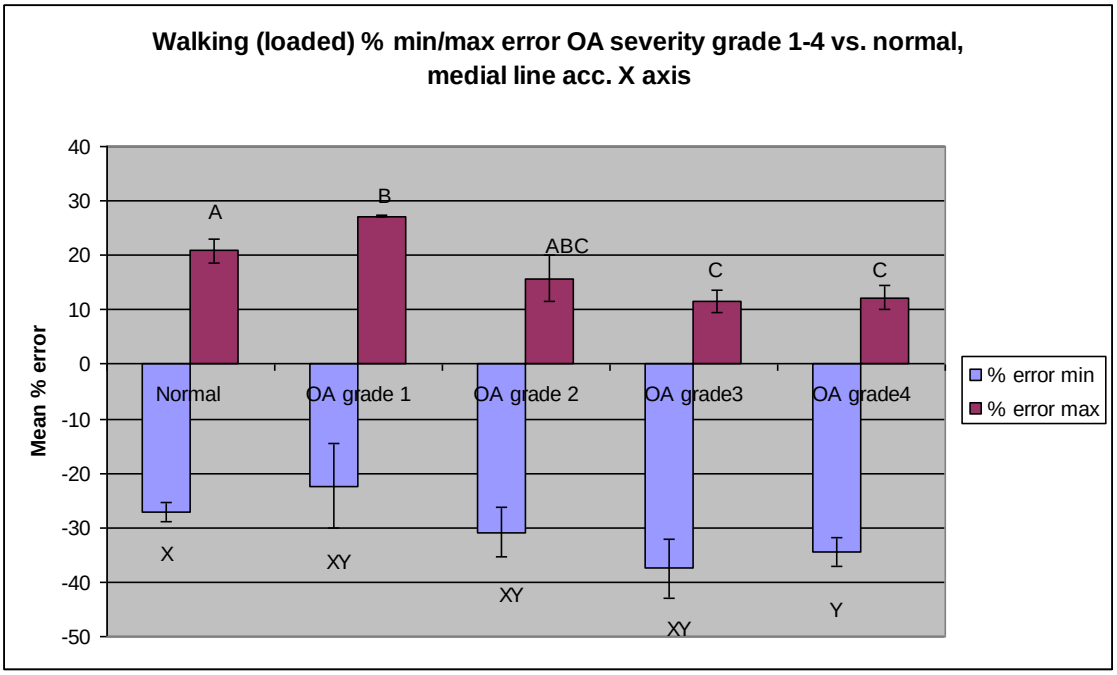


Figure 150. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

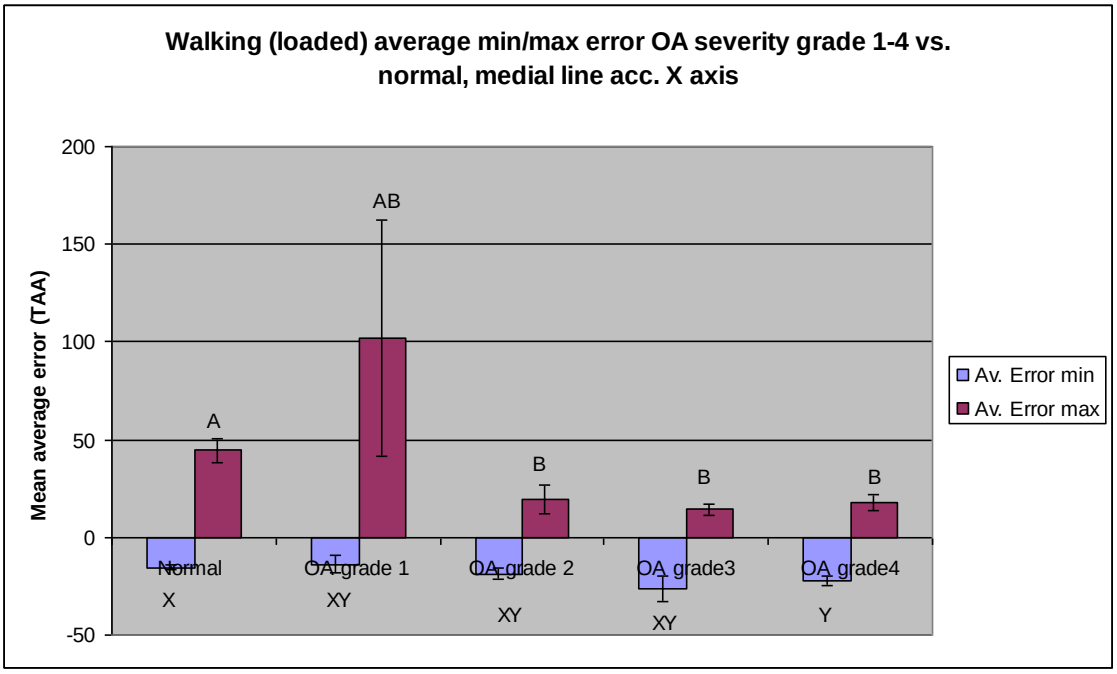


Figure 151. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

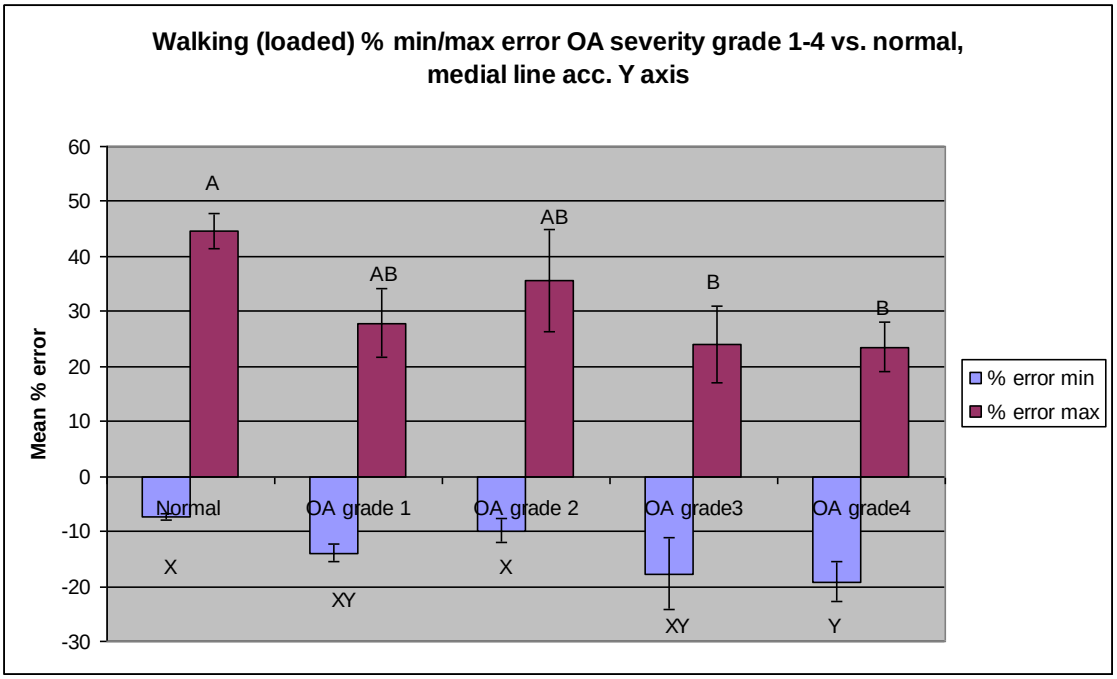


Figure 152. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

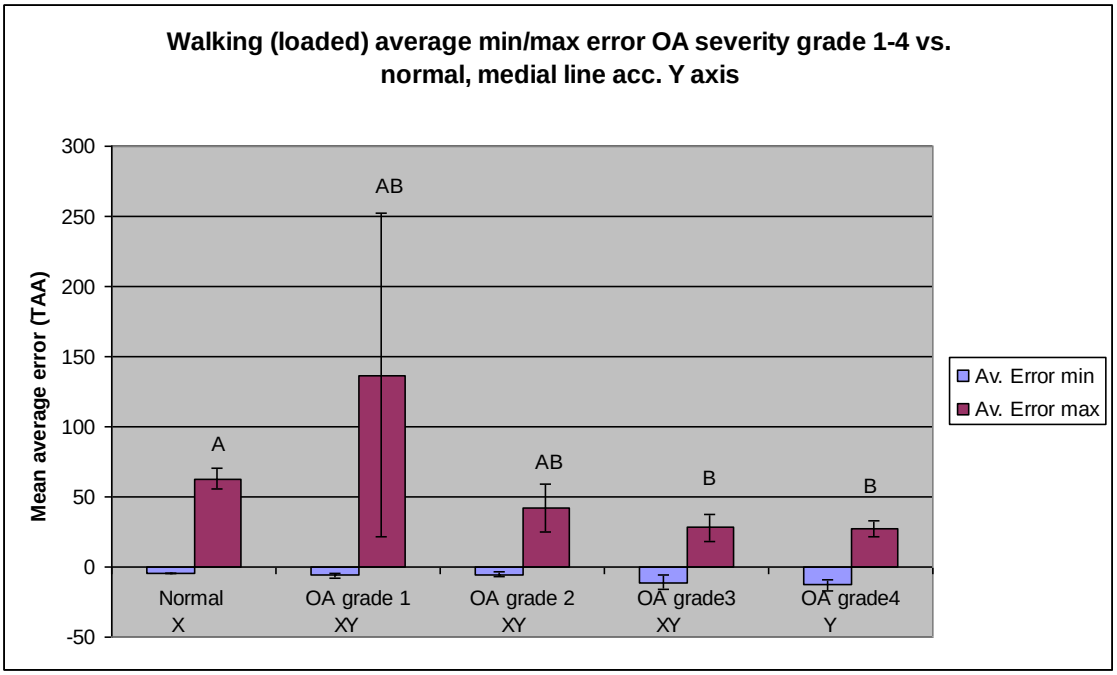


Figure 153. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

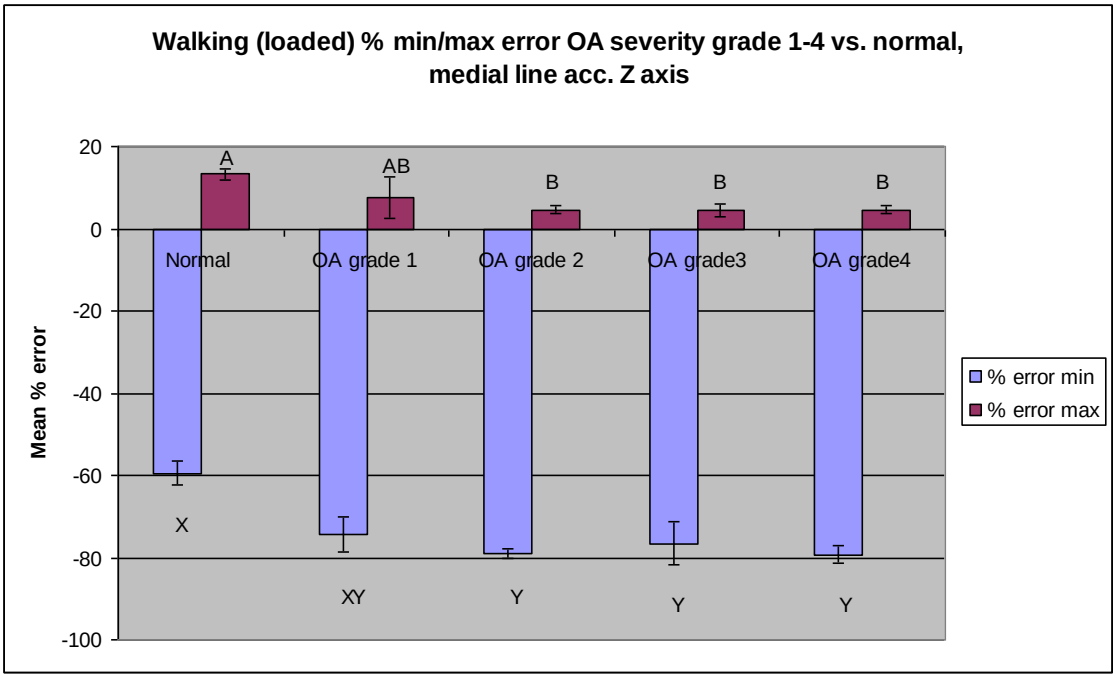


Figure 154. Mean values for walking (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

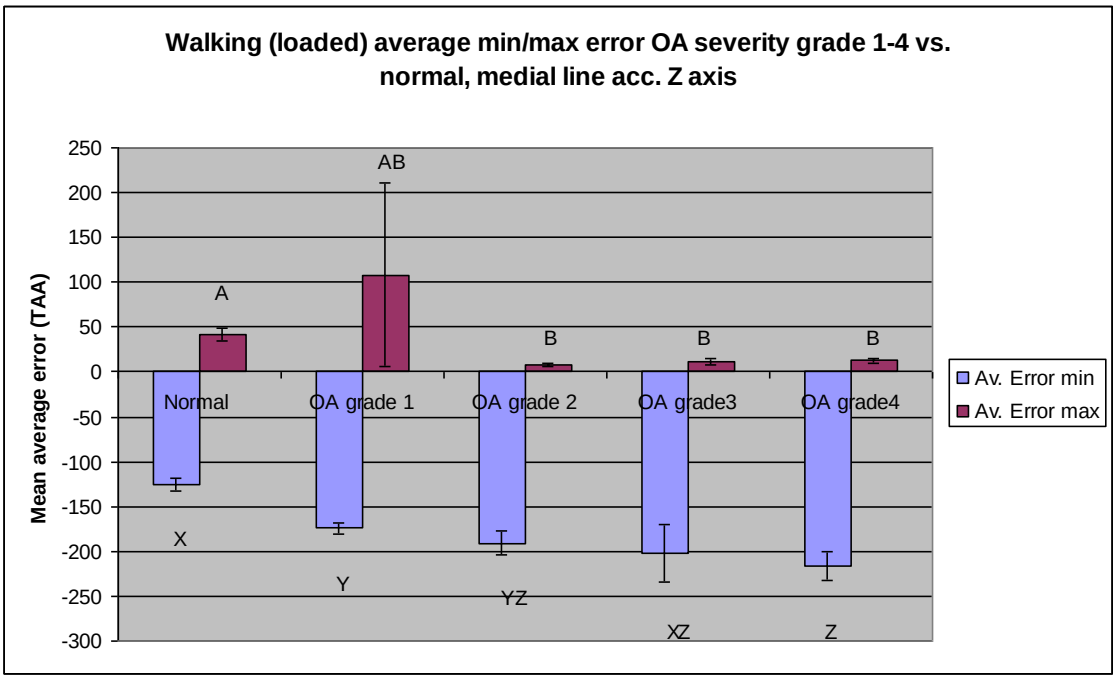


Figure 155. Mean values for walking (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 150-155 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the walking (loaded) protocol.

The X axis show significance differences in the values for % maximum error when normal is compared to grade 1, 3 and 4, grade 1 also differs significantly from grade 3 and grade 4. % minimum error values differ for grade 4 compared to normal. Average error maximum values differ when grades 2, 3 and 4 are compared to normal, average error minimum values differ when normal is compared to grade 4.
Y axis values for % error maximum differ when normal is compared to grade 3 and 4; % minimum values differ when normal is compared with grade 4 and when grade 2 is compared to grade 4.
Average error maximum values show significant difference when grade 3 and 4 are compared to normal, average error minimum values differ when normal and grade 4 are compared.
Z axis values for % error minimum and maximum differ significantly when normal is compared to grades 2, 3 and 4. Average error maximum values differ when grade 2, 3 and 4 are compared with normal. Average error minimum values differ when 1, 2 and 4 are compared to normal and when grades 1 and 4 are compared.

5.43: Sitting/rising (loaded), osteoarthritic grade 1-4 versus normal.

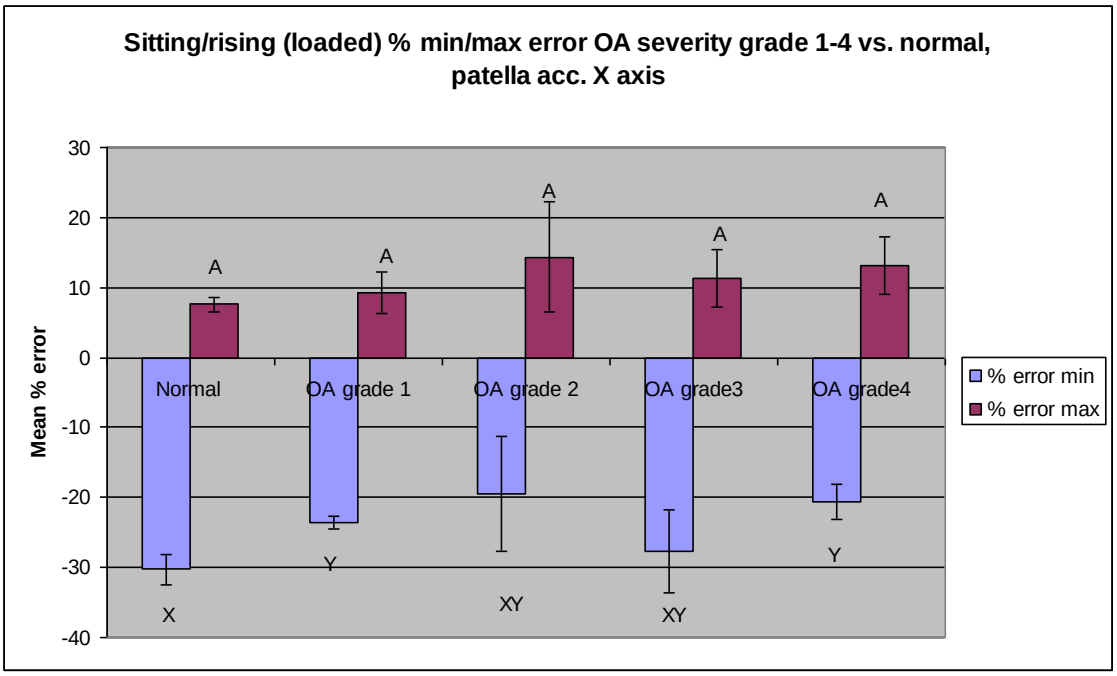


Figure 156. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

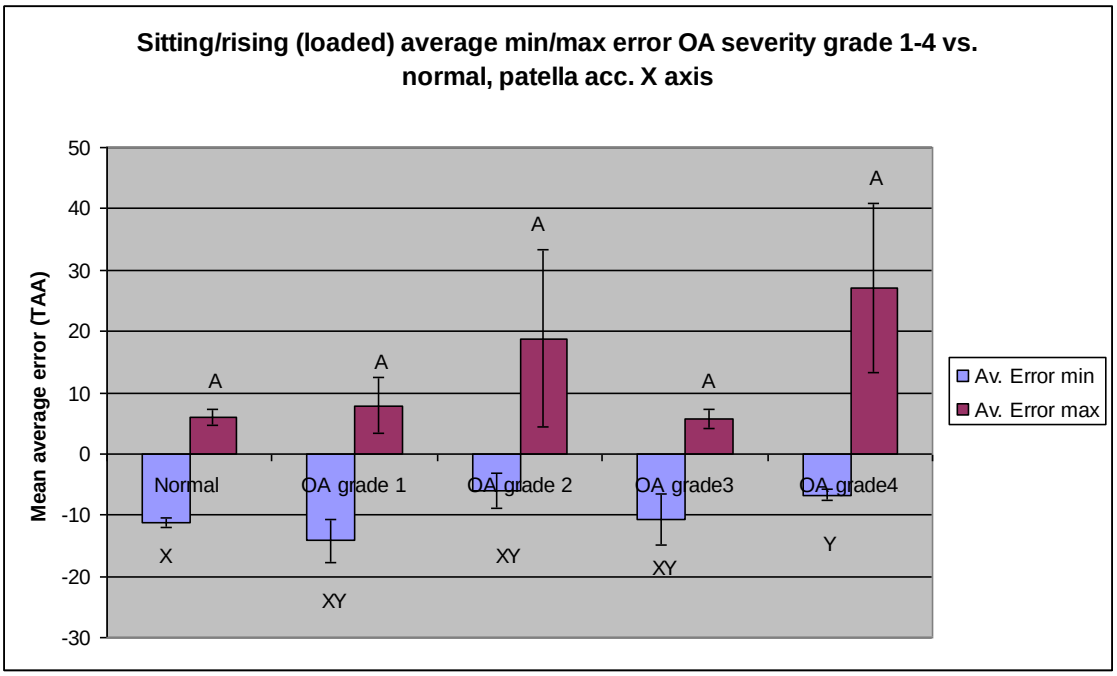


Figure 157. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the patella accelerometer.

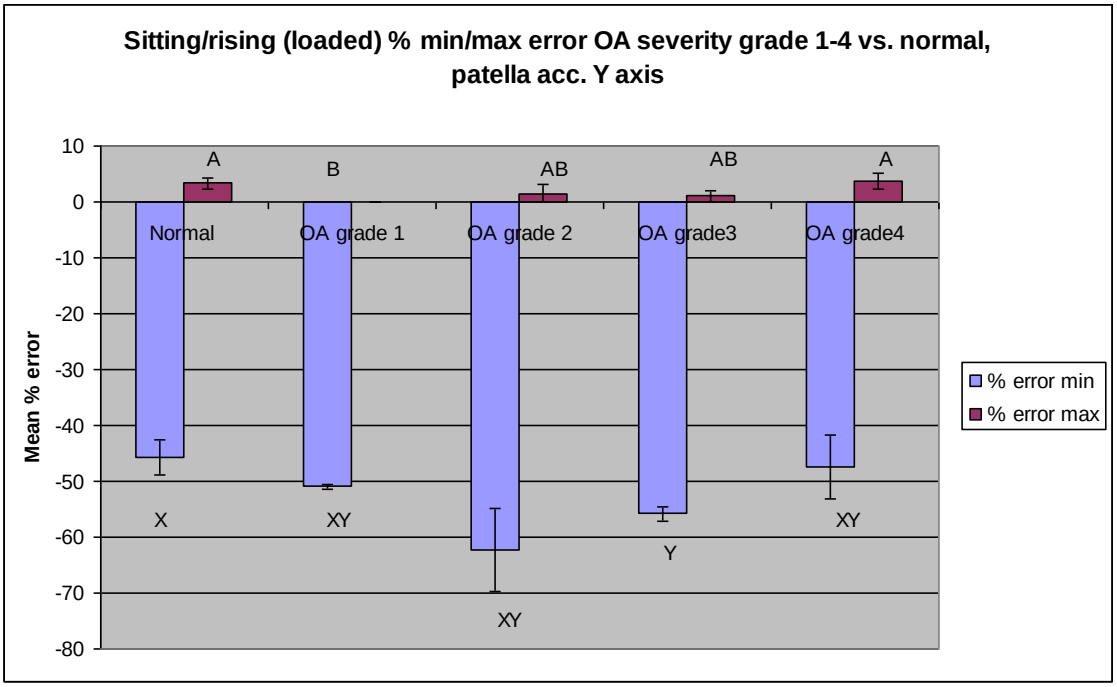


Figure 158. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

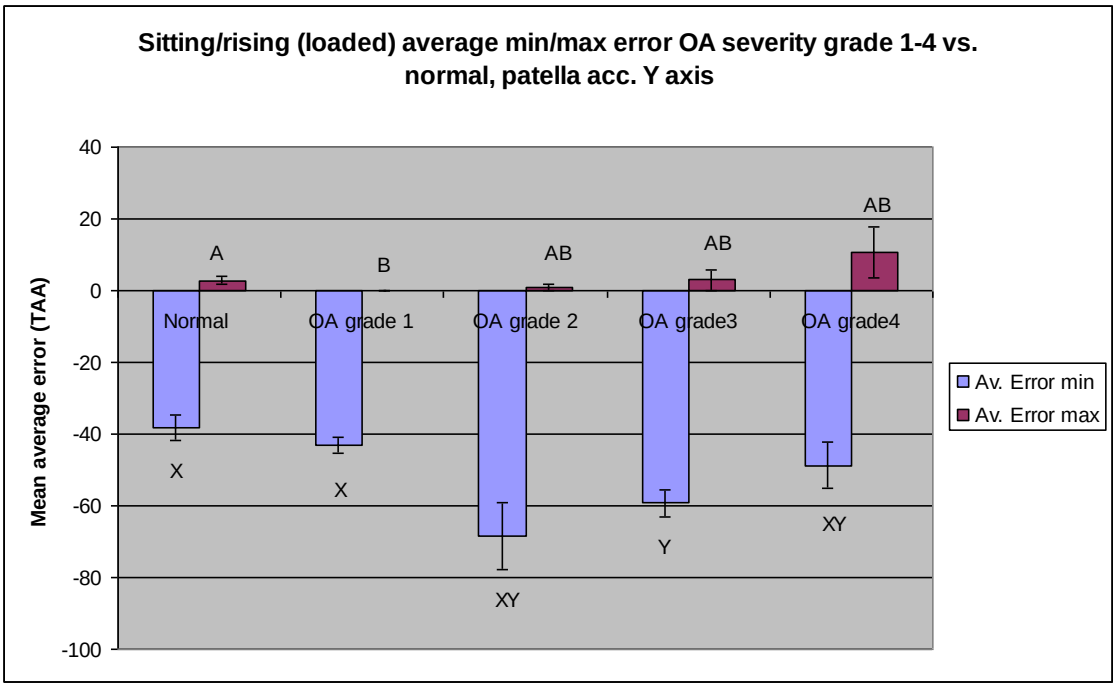


Figure 159. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the patella accelerometer.

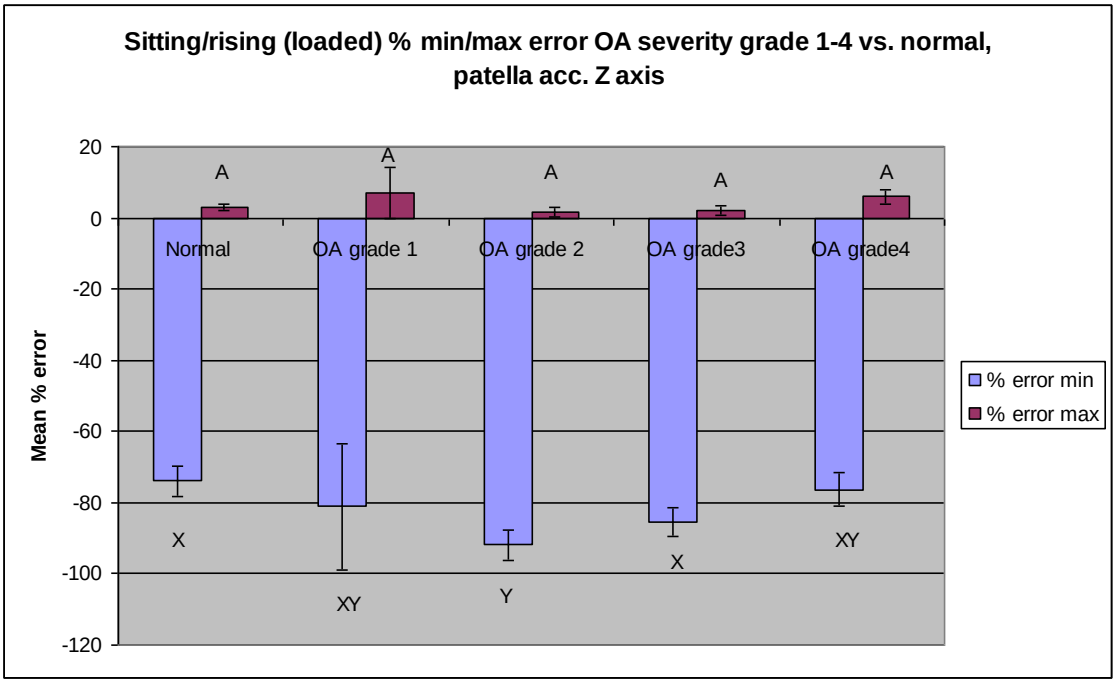


Figure 160. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

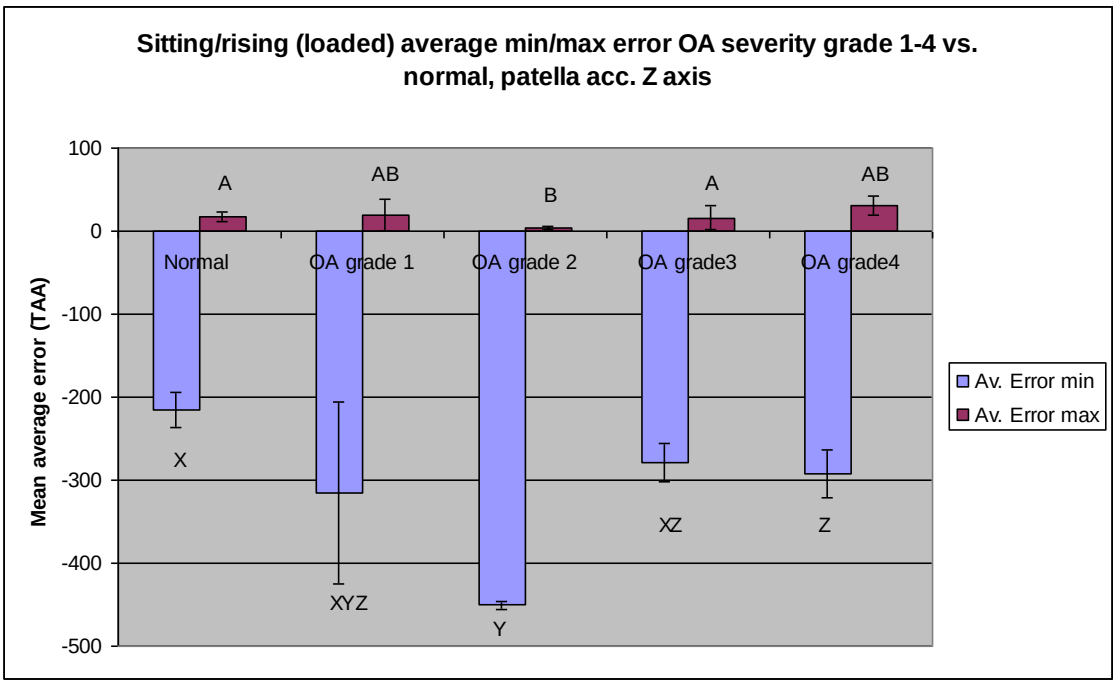


Figure 161. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the patella accelerometer.

The preceding figures 156- 161 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the patella accelerometer when performing the sitting/rising (loaded) protocol.

The X axis show significant difference between values for error minimum when grades 1 and 4 are compared with the normal group. Average error minimum values show differences between grade 4 and normal.
Y axis results show differences between the values for % error maximum when grade 1 is compared with normal and grade 4. % error minimum shows differences between normal and grade 3. Average error maximum shows differences between normal and grade1, average error minimum values differ when normal and grade 1 are compared to grade 3.
The Z axis results show significant difference between the values for % error minimum when grade 2 is compared with normal and grade 4. Average error maximum values differ when grade 2 is compared to normal and grade 4, average error minimum values differ when grade 2 is compared to normal, grade 3 and 4. Grade 4 also differs when compared to the normal group.

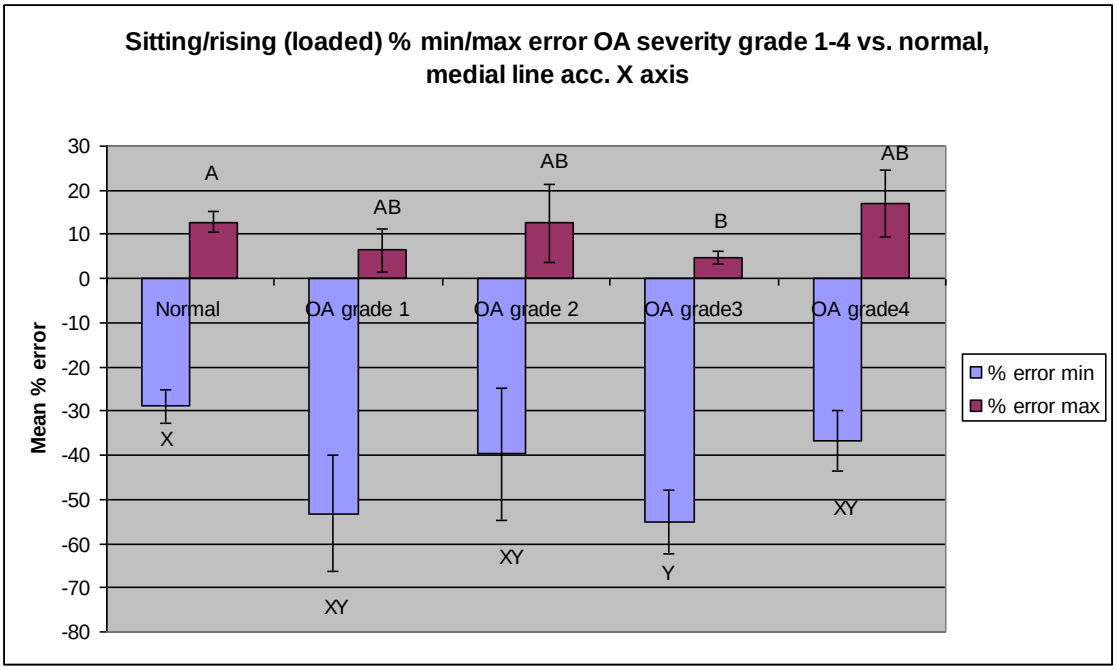


Figure 162. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

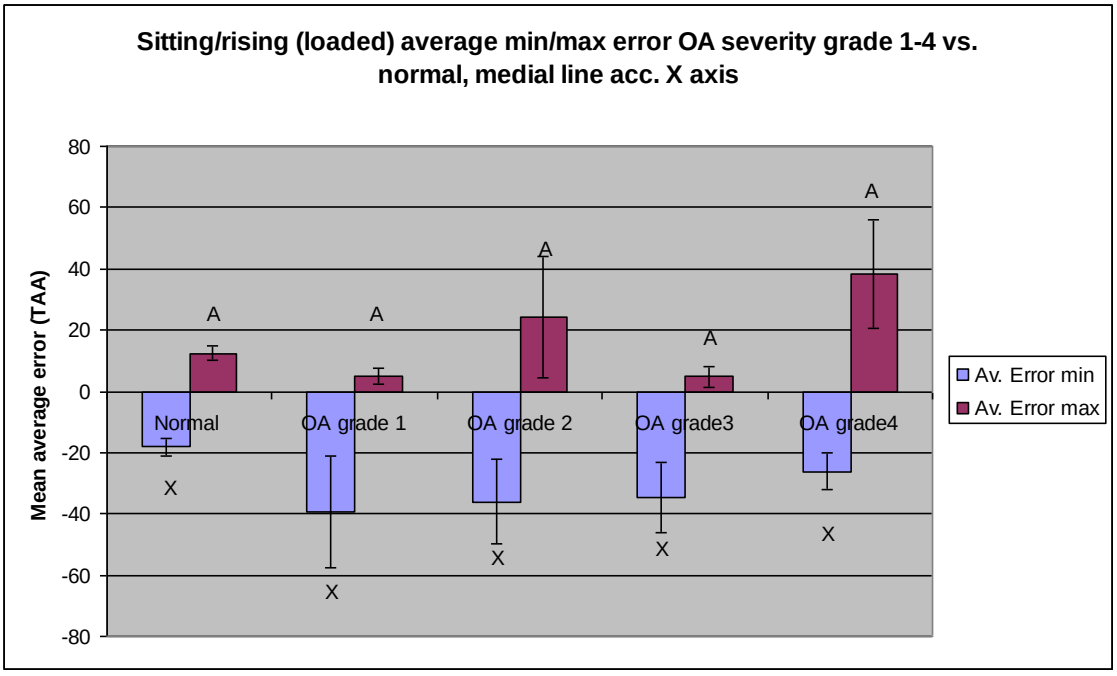


Figure 163. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, X axis of the medial line accelerometer.

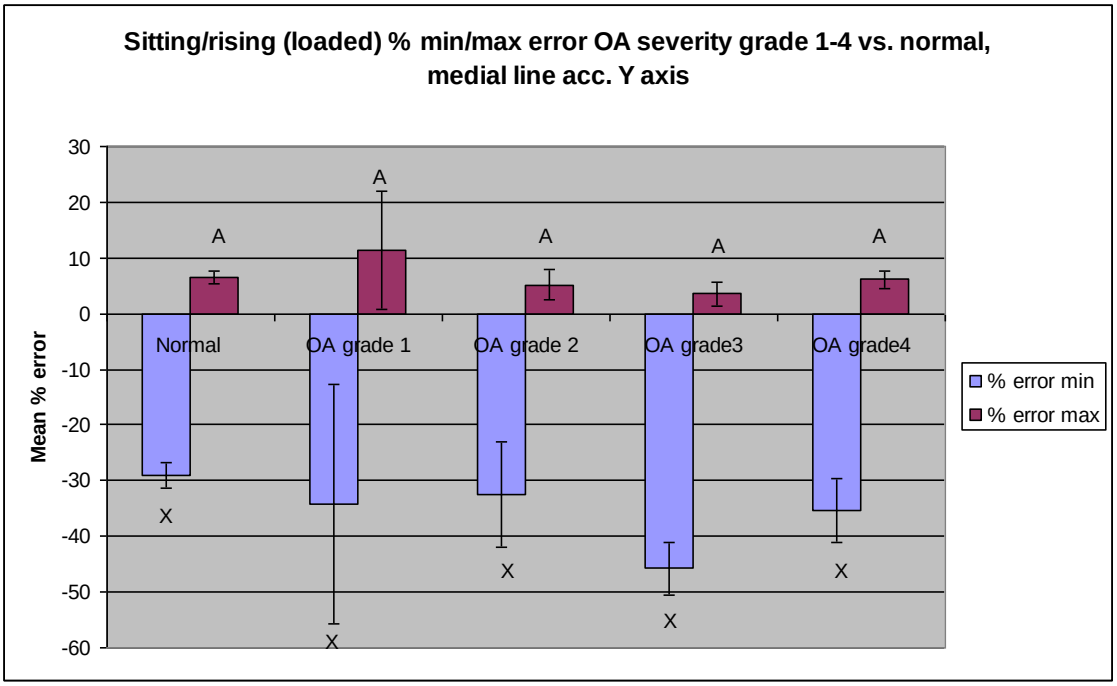


Figure 164. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

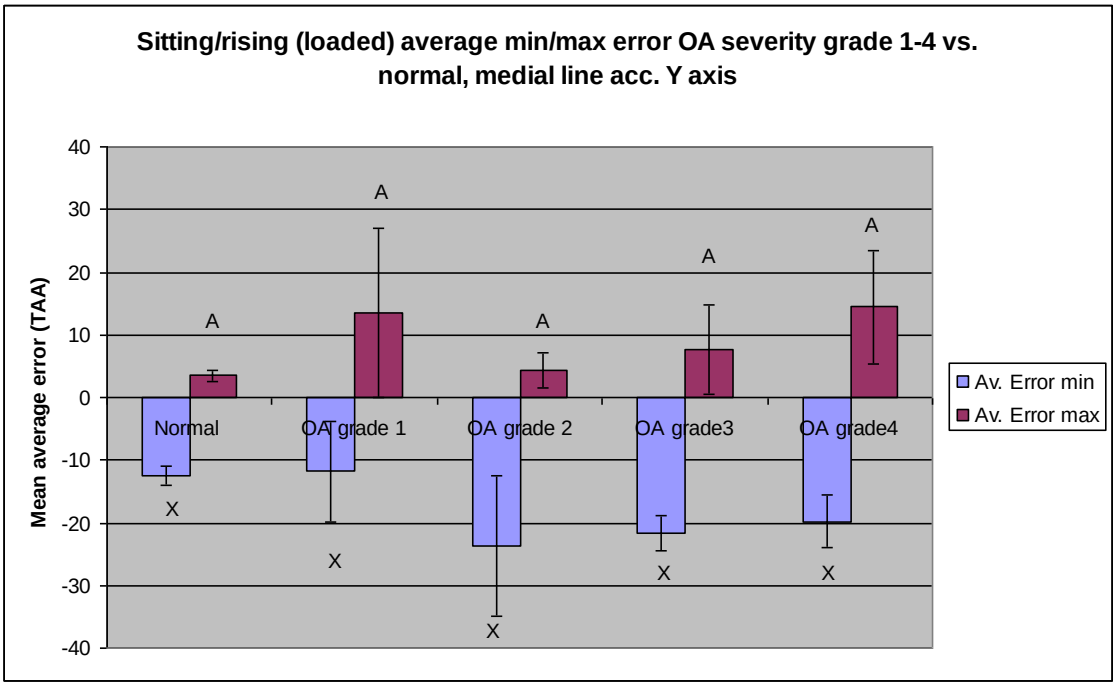


Figure 165. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Y axis of the medial line accelerometer.

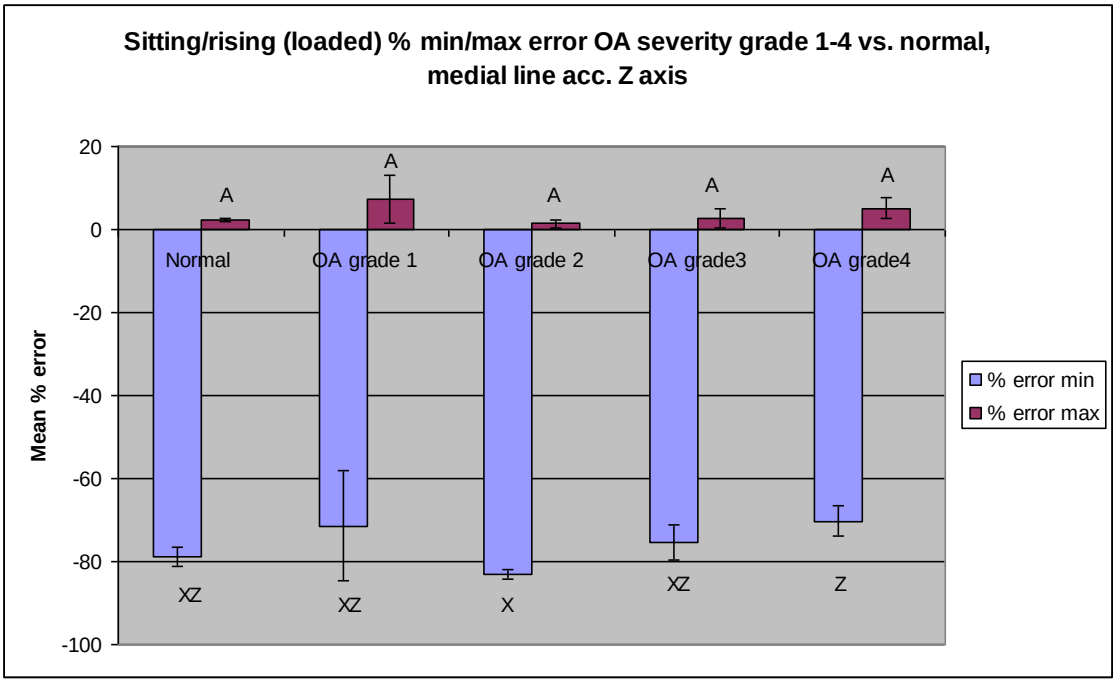


Figure 166. Mean values for sitting/rising (loaded) % min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

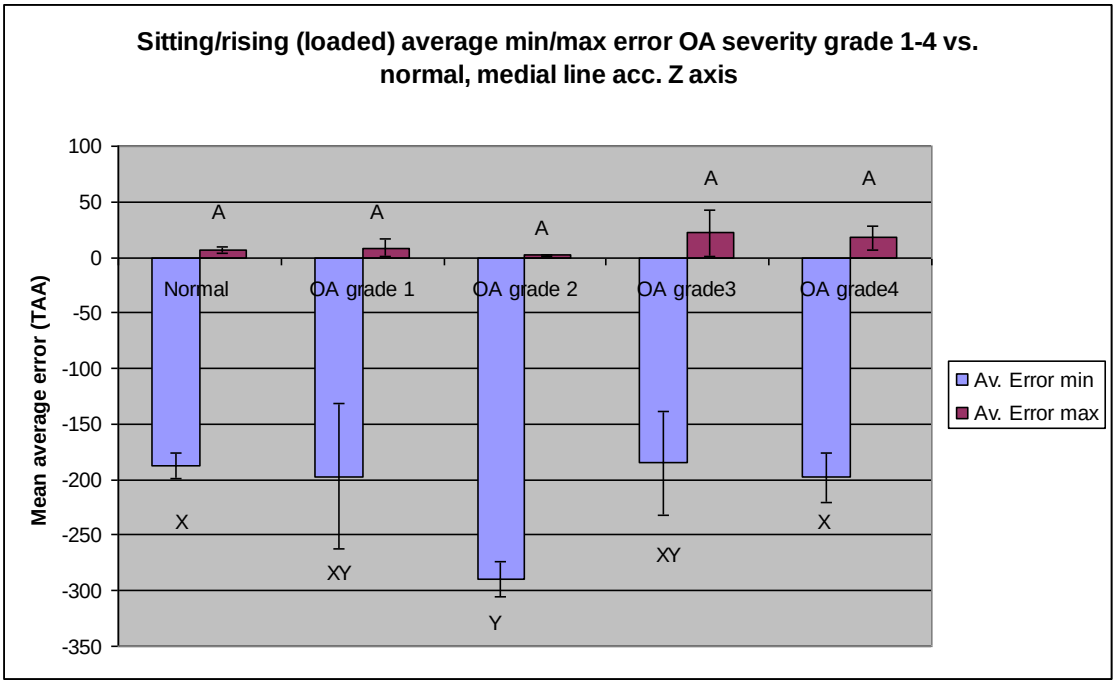


Figure 167. Mean values for sitting/rising (loaded) average min/max error, OA severity grade 1-4 vs. normal group, Z axis of the medial line accelerometer.

The preceding figures 162-167 show mean values for % error and average error for osteoarthritic grade 1-4 affected and normal knee groups. The results are taken from the X, Y and Z axes of the medial line accelerometer when performing the sitting/rising (loaded) protocol.

The x axis results show significant differences in the % error maximum values when grade 3 is compared with normal, % error minimum values show difference when normal and grade 3 are compared.
The Y axis of the medial line accelerometer shows no significant differences between the groups for %/average error maximum/minimum.
Z axis results show differences in the % error minimum values in the comparison of grade 2 and 4 groups. Average error minimum values showed differences when grade 2 was compared with normal and grade 4.

5.44: Discussion.

At this level of separation of the osteoarthritic data into subsets based on the progression of the disease within the joint, the results are not as clear in the delineation of the individual osteoarthritic groups from each other or from normal. Results that show significant differences are fewer than in either of the previous section and they are well dispersed within the datasets. As before, when considering the medial/lateral groupings, the evidence for the ability of the phonoarthrometer to differentiate between grades of osteoarthritis is lacking. Once again lower sample size and high standard error within the groups may have contributed to the lack of significant results. In particular the osteoarthritic grade 1 group exhibits these traits. Indeed osteoarthritic grade 1 diagnoses tended to be lacking this may be due to grade scores only be assigned by the clinician once the disease has progressed to a stage that requires a more serious intervention or procedure such as arthroscopy.

If the phonoarthrometer could be developed further to a point whereby an observable gradient in the results relating to severity is possible, then one theorised pattern would be that of a well defined gradient of suppression with most being found in osteoarthritis

grade 1 steadily decreasing in degree to osteoarthritis grade 4 and with all grades showing more suppression than found in the normal group.

However, direct observation of the given data values (although not statistically significant) for the extremes of the grades (1 and 4), suggests that there is more suppression related to the grade 1 osteoarthritic changes than for grade 4 osteoarthritic changes. In essence there could be greater suppression of the joint vibration signal found in the early stages of osteoarthritis than in the advanced stages of the disease. It could be theorised that this is due to greater swelling and inflammation in the cartilage and tissue of an early stage osteoarthritic joint. As the cartilage is worn away and other factors such as osteophyte formation and bone on bone wearing become more prevalent there is a tendency for the dampening effect caused the transmission pathway of the signal through the knee to be counteracted by the increased level of vibration signal from the source. As such this could result in a pattern whereby osteoarthritic grade 1 joints show the highest level of suppression, decreasing in a gradient to grade 4 osteoarthritis.
If this effect could be more conclusively proven by further development of the phonoarthrometer then this would be of clear clinical use, allowing osteoarthritis to be diagnosed at an early stage.

One thing to note is that these osteoarthritis grades are derived from the medical diagnosis of the participants and this in itself is a subjective process. Accepting that the physician giving the diagnosis is medically trained to accurately quantify the severity of osteoarthritis in the joint, then the assigned grades should be accurate. However, given that there is a substantial amount of literature dealing with monitoring and improving the accuracy of clinician's diagnosis of osteoarthritis (Park et al., 2013, Altman and Gold, 2007, Brenner et al., 2003); the assignment of osteoarthritic grades is subject to some level of inconsistency. A further point to note is that there is a time delay between the medical diagnosis of the participant's osteoarthritis and when the data was collected from the participant. The joint may therefore have degraded further during this period.

Chapter 6

Conclusions and further work.

6.1: Introduction.

In this, the final chapter of the thesis, a number of conclusions derived from the results will be provided and an assessment of the current operational capabilities of the phonoarthrometer will be offered.

The conclusions will be presented in a manner that addresses the aims of the study and that relates to the proposed hypotheses stated earlier. These in turn will allow an evaluation, within the data set examined, of whether the phonoarthrometer can be used to detect osteoarthritis in the human knee joint.

Following this a section is included that suggests further work required to develop the phonoarthrometer beyond its current prototype stage. Such recommendations will be stated with the aim of providing a logical sequence of progression towards this next stage.

6.2: Conclusions derived from the results.

6.21: Conclusions relating to the preliminary placement of sensors experiment.

The results from the preliminary experiment, in which the signal collection accelerometers were transposed to alternative locations around the selected placement positions, support the hypothesis that different points of attachment on the joint surface produce variability in the recorded acoustic signal. It can be inferred that this is due to the signal being altered as it passes through the structural impedances in its transmission pathway from the site of vibration generation to the signal collecting sensor. It would seem from this investigation that it is therefore correct to consider that the transmission pathway of the vibration through the knee joint has an effect on the signal.

The results showed that placement of the sensor at various places around the knee have a measurable effect on the recorded signal and that a level of variability is introduced to dependant on the placement of the accelerometers. The greatest effect was observed in the Y axis of the accelerometer, displacement by even 50% caused marked increases in the values for % error maximum and average error maximum.

The implications from these results are therefore of great significance to any future research that involves the placement of accelerometers at defined points on the knee joint (or for that matter on any joint being tested). The results presented here suggest strongly that incorrect placement of the sensors at points on the knee joint other than those carefully defined will lead to a change in the nature of the vibration response recorded, and that this in turn could result in the incorrect identification of a normal healthy knee joint as an abnormal one.

This has wide implications within this field of research as it means that placement of the sensors at repeatable well defined locations around the knee must have rigorous attention to accuracy. Failure to do so will lead to another level of variability being introduced into the resultant signal. Any analysis of the knee joint vibration signal must account for this, the fact that this issue regarding of the accuracy of sensor placement is not mentioned in the literature suggests that previous research has failed to identify it; as such this calls into question, to some degree, the results from past research in this field.

As a recommendation, all future work should include strict protocols relating to the accurate repeatable attachment of the sensors, so as to avoid this resultant uncontrolled variability being included in the recorded signal from the tested joint.

6.22: Conclusions relating to the detection of osteoarthritis within the knee joint.

Comparison of the results from the osteoarthritic versus the healthy normal knee group supports the hypothesis that osteoarthritic affected knee joints will produce a vibration signal differing to that of a healthy normal knee joint. It can be implied that such signal variation is a result of the differences between normal and osteoarthritic joint quality, with the vibration signal being further modified by various dampening and/or focussing

effects caused by any additional factors (such as inflammation of the joint) associated with osteoarthritis as the signal travels through the joint.

The results show that in actuality this is represented by an observed pattern of joint vibration signal suppression seen in the final statistical output from the osteoarthritic affected group data when compared to the normal knee group. This outcome is seen across all the various protocol groups and across all axes (X, Y and Z) of both the patella accelerometer and the medial joint line accelerometer. The phonoarthrometer, as such, shows an evident ability to detect osteoarthritis in a binary way.

This pattern of suppression is in itself an unforeseen result as it represents what can effectively be considered a quieting of the osteoarthritic joints in relation to the normal group knee joints. However a key point to remember is that the phonoarthrometer is not showing a quiet versus a loud joint signal, it is showing that the osteoarthritic group are exhibiting a quieter signal than is predicted by the phonoarthrometer software for a normal knee moving in the same way.

This may be considered counter intuitive to what would be expected from the osteoarthritic affected group, that an osteoarthritic knee joint with severe degeneration of the intra-articular cartilage should theoretically be noisier than a healthy normal knee joint. The reduction of cartilage, subsequent osteophyte formation and bone on bone abrasion should result in a greater amount of compression and friction within the joint, leading to an increased vibration signal from the knee joint. Indeed this is supported by the fact one recognised characteristic of advanced osteoarthritis in the knee joint is an audible crepitus (creaking) from the knee joint as it bends.

The fact that suppression of the joint vibration signal in the osteoarthritic affected knee group is actually the case bears further close consideration. One probable theory suggested is that degeneration of the knee joint intra-articular surfaces results in inflammation of the joint and an increased level of fluid accumulation in the joint synovial capsule, this excess fluid is then resulting in suppression of the vibration signal as it passes through it. Advanced articular cartilage damage within the joint causing cartilage and bone fragments within the synovial fluid, would add further factors that could suppress the vibration signal.

Another possible cause considered, is that the knee joint as it degenerates has lost much of the structural integrity that supports and stabilises the joint, resulting in the joint space widening between the distal tibial plateau and the femur. This would result in less contact between the bone ends and hence less noise/vibration. This theory would be well supported if the unloaded (flexion/extension swing) readings showed a significant pattern of suppression and the loaded (sitting/rising and walking) showed increased vibration levels; this however was not the case, and so throws doubt on the theory.

Whilst the actual cause the effect can only be theorised, it is a real effect as shown by the final statistical output from the phonoarthrometer. Although unexpected this high proportion of incidence of a suppressed joint vibration signals in the osteoarthritic affected knee joint group clearly differentiates the osteoarthritic group from the normal/healthy knee joint group.

Within the results there were also clear distinctions between the data collected from each protocol type. In general the results from the swing (unloaded) protocol were more conclusive and consistent than for walking and sitting/rising (loaded) protocols. This is due to a two fold effect, firstly the swing (unloaded) protocol produced longer angular sequences of flexion and extension and the phonoarthrometer software was able to process these better than the short sequences produced by the walking and sitting/rising protocols. Secondly, the microstructure library that was constructed for use in the analysis of the vibration responses was taken from swing protocol recordings. This meant that analysis of the walking and sitting/rising protocol data used only microstructures found in the swing protocol and therefore may be lacking some that would be found only in the loaded protocols. This may account for the observation that generally the loaded protocols showed higher levels of suppression for both osteoarthritic and normal data. This greater level of suppression could in itself be due to a greater level of lubrication in the knee caused by the increased pressure found in a loaded knee squeezing more synovial fluid from the cartilage as proposed by some theories of a dynamic lubrication regime within the knee.

6.23: Conclusions relating to determination of location of osteoarthritis within the knee joint.

The analysis of the data by the phonoarthrometer to determine whether it was possible to detect the location of the osteoarthritis within the knee joint, showed poor differentiation between the medial and lateral side of the knee, coincident to the location of the osteoarthritic damage.

The medial and lateral compartment osteoarthritic subset analysis revealed that no significant difference can be detected according to which side (medial or lateral) of the knee is afflicted by the osteoarthritic change

The pattern of suppression between the OA and normal groups was retained in a few examples; of more perceived importance would have been any detectable differences in the results for the medial and lateral group. There was however, only one instance where there are significant differences recordable between the medial and lateral side of the joint.

6.24: Conclusions relating to the severity of osteoarthritis within the knee joint.

The results do not support the hypothesis, that the grade of severity of osteoarthritis (as determined by the clinicians diagnosis using the Kellegren-Lawrence scale) within the knee joint affects the transmission pathway of the vibration response through the knee in such a way that differences in the collected vibration response can be observed.

The results are not sufficiently conclusive and consistent to allow an observed pattern to be deduced that would allow the severity of osteoarthritis in the joint to be categorised. Whilst, the results were not conclusive in proving detection of osteoarthritic severity, some difference was noted between the extremes of severity (Grade 1 and 4) in a few specific cases. .

As noted previously, in some instances, if the extremes (1 and 4) of the Kellegren-Lawrence grades are taken there is more suppression related to the grade 1 osteoarthritic changes than for grade 4 osteoarthritic changes. In essence there is greater suppression of the joint vibration signal found in the early stages of osteoarthritis than in the advanced

stages of the disease. It could be theorised that this is due to greater swelling and inflammation in the cartilage and tissue of an early stage osteoarthritic joint. As the cartilage is worn away and other factors such as osteophyte formation and bone on bone wearing become more prevalent there may be a tendency for the dampening effect caused the transmission pathway of the signal through the knee to be counteracted by the increased level of vibration signal from the generation source. This observation could provide a theoretical starting point for development of the phonoarthrometer into a more clinically useful device; as if this effect could be more conclusively proven by further research then this would allow osteoarthritis to be diagnosed at an early stage.

6.25: Summary

The phonoarthrometer at its prototype stage has the evident ability to differentiate between an osteoarthritis affected knee joint and that of a normal/healthy knee joint, but it cannot at this stage differentiate between medial and lateral compartment osteoarthritis within the knee or show differentiation in the osteoarthritic severity grading results.

This suggests that even in this prototype stage the phonoarthrometer has potential for development to a clinically useful device as it currently has the ability to detect osteoarthritis within the tested data set, however, it most likely does not possess enough focus within the processed output to in reality be fully embraced by the medical establishment, for this to happen the device would be required to produce a more definitive and detailed diagnosis than it is currently capable of.

As one further point, during the course of the study it was mentioned by a clinician that a diagnostic device that could confirm that pain experienced in the knee joint was from the damaged articular surfaces in the joint and not referred pain from the nerves in the spine would be of use, as many patients often experience pain in their knees that can ultimately be due to compressed nerves in the spinal column. To this end a medical device, such as the phonoarthrometer at a slightly more developed stage, may be viable for placement in GPs surgeries. This early stage device would theoretically be used to confirm or refute that the pain experienced by the patients was indeed from the knee joint and not from the nerves in the spine.

6.3: Further work.

The main purpose of this section is to give recommendations for further work that will focus the operational capabilities of the phonoarthrometer software and lead to an increase in its ability to detect a variety of conditions within the knee joint.

The proposed further work can be broadly categorised into the two following sections; the first provides a number of recommendations that should be implemented in order to improve the operational ability of the phonoarthrometer software, the second proposes further experimental work to test currently unknown factors.

As such there is a degree of crossover in the nature of the proposed work, as many of the recommendations will require some level of experimental testing and it is envisioned that the results from the experiments will lead to knowledge that will be used to improve the detection ability of the phonoarthrometer.

Recommendations to improve the operational ability of the phonoarthrometer are:

1) There is the need for the building of comprehensive and well stabilised (saturated) microstructure libraries for standard use in the future. This should be undertaken for all three motion type protocols (flexion/extension swing, sitting/rising and walking) if they are to be used for future studies. Along side the creation of these further microstructure libraries, an experiment should be carried out that assesses the effect of these databases on the processing of data.

2) A move to a higher sampling rate is also recommended. Increasing to a greater level of sampling rate would eliminate the data gaps encountered as described previously in chapter 3. A level of extra experimentation would be necessary here, involving a careful consideration of how increasing the sampling rate affects the core software operation. This should be made with regards to any changes observed to the recorded raw data traces and subsequent processing at the various sampling rates.

3) A comprehensive historic database of normal responses should be built for future reference in all research. This would be comparative with other research active in the field of joint vibration signal analysis. More importantly this would effectively standardise the core normal data used across all future research. This standard normal database would be specifically related to the phonoarthrometer. The use of a pre-constructed standard database of normal responses for use with future research, would allow future researchers to fully concentrate on the aspect of the phonoarthrometer that they were investigating rather than having to re-gather data from normal knee joints for each piece of research.

This is not to say that once gathered this should be the only collection of data, merely that it should form a core database of normal knee joint vibration responses for future studies. This database, if possible, should include enough individuals to take into account the variation in the biometric parameters. It would seem sensible that windows of range are set for each biometric parameter to provide sufficient sample sizes for use, for instance the age parameter should be divided into windows of 5 year groupings and the weight parameter 5 kilogram groupings. This is believed to be a very important way to enhance the focus of the phonoarthrometer as it would effectively unlock the biometric parameters of the phonoarthrometer allowing a greater level of variability to be accounted for in the given prediction.

Within this recommendation, it is suggested that the ‘activity level of the individual’ biometric parameter should be carefully re-assessed. This has never sat particularly well within the scheme of the phonoarthrometer, as it is a qualitative piece of data and therefore subjective to the individual. Frequently during the course of the experiment Individual’s recorded higher values for this than possibly was the case. The main reason being that a fit and active sixty year old would see themselves as being much more active simply swimming once a week and playing golf, rather than a twenty year old that biked five or more miles to work every day. The opinion is that this function is without doubt necessary for the use of the phonoarthrometer but that in order for it to be viable a level of objectivity must be introduced.

4) It is also recommended that attention is paid to the zeroing problem as previously identified (Chapter 4). One possible and practical solution to this is to pre-zero the

electro-goniometer using a straight edge such as a ruler on a table. Simply this would involve lining up the electro-goniometer to a straight edge and zeroing it. The electro-goniometer would then be attached to the leg as per the normal instructions given. It would be wise to still include the engagement of the screw home mechanism at this point to ensure where possible that the electro-goniometer is attached in a standardised way.

As a last general point all of the above mentioned recommendations should be implemented with caution. Any changes made should seek to enhance the phonoarthrometers' ability and not to detract from it or essentially change the previously developed core principals on which the phonoarthrometer was built.

Proposed further experimental investigation:

1) The results from the placement of the accelerometer sensors experiment presented the question of whether the positions denoted for use in this study (and other literature) are necessarily the optimum locations on the knee joint for attachment, in terms of collection of the vibration signal. It is probable that within any alternative attachment locations there is the potential to enhance the vibration response collected from the knee. If this is indeed the case, any future development of the phonoarthrometer would be wise to devote additional research time to such an investigation aimed at determining the optimal placement positions for the accelerometers to gather the vibration signal from the joint. In order to test this, the experiment should be expanded considerably to assess a wide variety of attachment points and form this determine anatomical locations on the knee joint that enhance the collection of the vibration response from the joint. Within this assessment consideration should be given as to the mechanisms behind the causes of enhancement (or indeed reduction) of the vibration signal occurring. As a theoretical example, if the signal collection is maximised at the edges of the patella, is this due to focussing effects related to its shape. Such consideration could aid in the selection of attachment sites for studies involving other joints.

2) As proposed in chapter 3, an experiment to conduct a range of tests that recorded the length of time taken for the participant to complete individual flexion/extension sequences within the swing protocol would be informative. The variability in the speed of movement in the knee joint has been widely commented on in the literature and as of yet

attempts at controlling it have been ineffective. The original development of the phonoarthrometer recognised this and as such its operation was designed to require no constraint upon the speed that the knee joint moves through an angular arc. However, post development of the phonoarthrometer; testing of whether the speed of the knee joint has any effect on the resultant data, has not been investigated. It must be understood that the purpose of this experiment is not aimed at controlling the speed of the knee in the future use of the phonoarthrometer; its purpose would be to determine whether differing rates of joint movement affected the resultant data produced. This experiment would involve varying the timing for the completion of individual flexion/extension sequences, with deliberate recreation of extreme fast and slow examples necessary. These could then be assessed as to whether there is any affect on the final data produced. Within this experiment an analysis of the microstructure motion types identified by the phonoarthrometer should be included, in order to determine whether specific timings for the speed of movement of the knee joint access specific microstructure types.

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6.4: Concluding remarks.

In general the research presented here shows an encouraging and positive future for the use of phonoarthrometry and in particular the use of multi-dimensional analysis to detect joint problems. It s believed that this piece of research can only enhance this process and set the first step on the phonoarthrometers' path to a fully effective clinical tool.

The study presents the first clinical use of the phonoarthrometer for the detection of a specific condition, osteoarthritis, before this only a handful of arbitrarily determined case studies had been investigated using the phonoarthrometer.

The results of this study conclude that knee joint osteoarthritis can be detected and that it can differentiate locations of the disease within the joint, however, with regards to detecting specific severity levels the phonoarthrometer is not sufficiently focused at its current developmental stage to be of clinically useful value.

The research shows conclusively that the core values established in the development of the phonoarthrometer are accurate and viable for future development. The basic underlying design of the system does not therefore need to be completely rethought. It is

however recommended that aspects of the phonoarthrometer need to be carefully examined with a view to progressing the device to the next stage in its development. Careful consideration of the phonoarthrometer is needed to develop a more fully focused device with a more comprehensive ability to detect osteoarthritis (or any other joint condition). If this is achieved then a clinically valuable device will undoubtedly be the result.

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Appendix 1: Participant information sheets, questionnaire and consent form.

Faculty of Health and Social Care
Anglia Ruskin University
East Road
Cambridge
CB1 1PT

Testing of the Phonoarthrometer

Information Sheet

(For Staff and Students)

We would like to invite you to take part in our research study. Before you decide we would like you to understand why the research is being carried out and what it would involve for you. Please take time to read the following information carefully. Talk to others about the study if you wish.

(Part 1 tells you the purpose of this study and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of the study).

Ask us if there is anything that is not clear or if you would like more information. Should you wish it, one of our team will go through the information sheet with you and answer any questions you have.
Once you have done this please take some time to decide whether or not you wish to take part.

Part 1

What is the purpose of the study?

Joint injury and disease are very common; they affect people of all ages, though especially older people. At present, patients are examined with large and expensive devices such as MRI or CT scanners to help identify what is wrong. This study will be concerned with testing a prototype medical device previously developed at Anglia Ruskin University, called a phonoarthrometer, which simply listens to the sounds your knee joint makes as it moves naturally to identify any problems.

This project is designed to test the phonoarthrometer's ability to specifically detect Osteoarthritis in the knee. However, for this part of the study we are recruiting participants with knee joints that can be considered normal so as to compare these readings with the data collected from Osteoarthritic knees.

Can I participate?

In order to participate to participate in this study your knee joint must be considered normal by the following criteria:

1) Your Knee must currently be free from pain
2) You must never have experienced serious injury requiring surgery to your lower body (from the waist downwards)

If the answer is yes to both these questions then you are eligible to participate.

Do I have to take part?

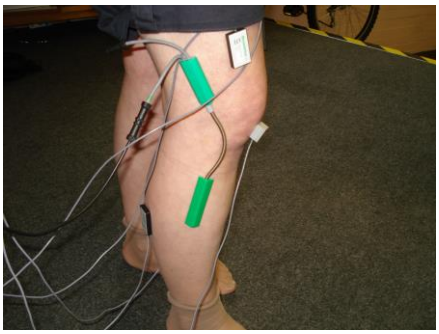
No. It is up to you to decide if you wish take part. If you agree to take part but later change your mind you are free to withdraw from the study at any time. If you wish to withdraw please inform George Bocking by e-mail or telephone at the given contact details in part 2.

What will happen to me if I take part?

If after reading this leaflet you wish to be part of the study you will be asked to sign a consent form. Signing the consent form will not affect your right to withdraw from the study if at a later date you change your mind.

You will also be asked to fill out a short questionnaire asking you about any previous pain or injury to your knee joint, your date of birth, sex, height, weight and level of physical activity. We will ask you to supply contact details for your normal GP.

You will then be invited to attend a one off session, run within the Helmore building, Anglia Ruskin Cambridge campus, at time convenient to you.
This session will take approximately 30 minutes. During the session sensors will be attached to you leg (see picture below)



It is vital that you wear shorts or other suitable clothing that allows you to bare your knee, as the sensors must be in contact with skin, and impacts from clothing can disrupt the readings. You will then be asked to move your leg in a normal way in a sequence of movements as described in the next section of this leaflet.

After the sounds from your knee have been recorded the sensors will be removed and this will be the end of the session.

What will I have to do?

You will be asked to sit and swing your lower leg while the sensors placed on your knee record the sounds it makes as it moves. You will be asked to swing your leg back and forth up to 10 times, and will repeat this activity up to 5 times. You will also be asked to rise and reseat yourself into a chair 3 times and to walk 5 paces forward turn and walk a further 5 paces back to your starting position. There will be a brief rest between each of these activities. If at any time you start to feel discomfort you should stop the activity at once.

What are the possible disadvantages and risks of taking part?

There is little risk involved in having these measurements taken. Agreement to participate in this research should not compromise your legal rights should something go wrong.

What are the possible benefits of taking part?

Inclusion in the study will not have a direct benefit for you as a participant; however, it is hoped the information we get from this study may help to make the future diagnostic process for detecting Osteoarthritis faster and less invasive in others.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. The detailed information on this is given in Part 2.

Will my taking part in the study be kept confidential?

Yes. We will follow ethical and legal practice and all information about you will be handled in confidence. The details are included in Part 2.

Part 2

What if relevant new information becomes available?

In the unlikely event that new information becomes available that will affect your continued participation in this study this will be passed on to you as soon as it becomes available.

What will happen if I wish to be withdrawn from the study?

If you wish to be withdrawn from the study we will need to retain and use the data already collected, up until the point of your withdrawal. No further data will be collected or any other research procedures carried out on or in relation to you.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. Please raise your concerns in the first instance with the Principal Investigator; George Bocking, contact details are at the end of this form.

If you remain unhappy and wish to complain formally you can do this through.
In the event that something does go wrong and you are harmed during the research and this is due to someone's negligence then you may have grounds for a legal action for compensation against Anglia Ruskin University but you may have to pay your legal costs.

What will happen to the results of the research study?

The actual sound recordings of the knee in motion may form part of the detection system, therefore data collected may be integrated into the actual device. This data will be fully anonymised and cannot be related to you as an actual participant in the study.

The results of this study will be analysed to assess the use of the equipment. They will be written up as an academic report and published in academic journals. The results will be fully anonymised and cannot be related to you as an individual in the study.
Should you wish, you can be informed of the progress of the project by letter.

Will my taking part in the study be kept confidential?

All information and measurements collected from you will remain confidential to the development team. To protect your personal information you will be assigned an ID number from your consent form and all records of your data will use this. Consent forms will be kept in a locked cupboard in the researchers locked office; the collected data will be stored on a password-protected database at the university.

Will my General Practitioner/Family Doctor (GP) be involved?

We will ask you to supply contact details for your normal GP.

Your GP will not normally be notified that you are taking part in this study, but there is a small chance that results from this study may suggest you have a condition of which you are unaware. This will not be a diagnosis but it may suggest further standard clinical tests should be run just to be sure. In such circumstances we will contact your GP and at their discretion you will be referred to the appropriate specialist after consultation with your general practitioner. Such detection has the benefit of starting treatment early.

Who is organising or sponsoring the research?

The research is being funded and organised at Anglia Ruskin University by a project team under the leadership of Dr Steven Abbott.

Who has reviewed the study?

This study concerns research carried out both at Anglia Ruskin University and within the NHS therefore it has undergone review by a NHS Research Ethics Committee.

All research in the NHS is looked at by independent group of people, called a Research Ethics Committee, to protect your interests. This study has been reviewed and given favourable opinion by the Norfolk Research Ethics Committee.

Further information and contact details:

Thank you for reading this information leaflet. If you have problems or questions now or during your treatment, please do not hesitate to get in touch.

Please use one of the following email addresses or contact numbers:

George Bocking (principal investigator)
Tel: 0845 196 2122
E-mail George.Bocking@student.anglia.ac.uk

Faculty of Health and Social Care
Anglia Ruskin University
East Road
Cambridge
CB1 1PT

Testing of the phonoarthrometer

Information Sheet

(For Consultants/GPs)

We would like to invite you to be involved in our research study. This information sheet outlines why this research is being carried out and what it would involve for you. Please take time to read the following information carefully. Talk to others about the study if you wish.

(Part 1 tells you the purpose of this study and what will happen to participants in the study. Part 2 gives you more detailed information about the conduct of the study).

Please do not hesitate to ask us if there is anything that is not clear or if you would like more information. Should you wish a more detailed explanation, one of our team will go through the information sheet with you and answer any questions you have.

Part 1

What is the purpose of the study?

phonoarthrometry is the study of sounds produced naturally by a joint in motion. This study will be concerned with testing a prototype medical device previously developed at Anglia Ruskin University. The prototype device, termed a phonoarthrometer, enables the sounds produced by the human knee in motion to be analyzed and when compared to the predicted reading that a normal knee produces it theoretically enables a range of joint disorders to be detected. In this study it will only be attempting to detect Osteoarthritis in the human knee. The study will test the device on participants suspected to have Osteoarthritis. It will seek to identify how the phonoarthrometer responds to Osteoarthritic knee data and how this differs from the patterns seen in normal knee data. The study will then involve testing the device under blinded conditions, collecting data from undiagnosed participants to evaluate the accuracy of phonoarthrometry in detecting Osteoarthritis. The results of the phonoarthrometry will be compared with that produced by normal means, no access to MRI scans or other data will be permitted, and a short report will be written of the findings from phonoarthrometry permitting a judgment to be made on how useful the phonoarthrometer was in each case.

Do patients have to participate?

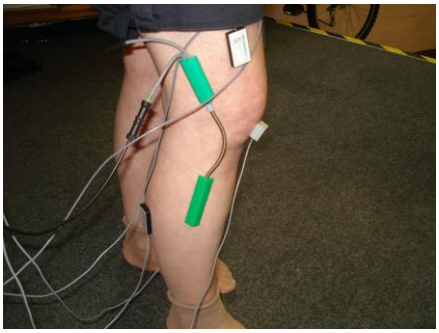
No. It is up to a patient to decide if they want to participate. A patient is free to withdraw from the study at any time, without giving a reason. This will not affect the standard of care they receive.

What will happen to the patient if they take part?

If they agree to take part, we will send them detailed information about the study (Participant Information Sheet) and ask them to sign the consent from if they decide to take part. Signing the consent form will not affect the patients right to withdraw from the study at a later date.

They will also be asked to fill out a short questionnaire asking you about any previous injury to the knee joint, their date of birth, sex, height, weight and level of physical activity.

The participant will then be asked to attend a one off session run along side their planned normal care.
This session will take approximately 30 minutes. During the session sensors will be attached to their leg (see picture below).



It is vital that the participant wears shorts or other suitable clothing that allows them to bare their knee, as the sensors must be in contact with skin, and impacts from clothing can disrupt the readings. The participant will then be asked to move their leg in a normal way in a sequence of movements as described in the next section of this leaflet.

If they normally require a walking aid, such as a stick, they will be allowed to use it.

After the sounds from the knee have been recorded the sensors will be removed and this will end the session.

What will participants have to do?

They will be asked to sit and swing their lower leg while the sensors placed on the knee record the sounds it makes as it moves. Participants will be asked to swing their leg back and forth up to 10 times, and will repeat this activity up to 5 times. They will also be asked to rise and reseat themselves into a chair 3 times and to walk 5 paces forward turn and walk a further 5 paces back to the starting position. There will be a brief rest between each of these activities. If at any time the participant starts to feel discomfort they should stop the activity at once.

What are the possible disadvantages and risks to the participant in taking part?

There is little risk involved in having these measurements taken. Agreement to participate in this research should not compromise participant's legal rights should something go wrong. There is a risk that the motions of the leg being requested will be excessively uncomfortable for a participant. If they feel discomfort from any of the movements requested, they will be informed that they should request to stop at once.

What are the possible benefits for the participant in taking part?

Inclusion in the study will not have a direct benefit for the participant; however, it is hoped the information we get from this study may help to make the future diagnostic process for detecting Osteoarthritis faster and less invasive in others.

Will a participant's personal information be kept confidential?

Yes. We will follow ethical and legal practice and all information about a participant will be handled in confidence. The details are included in Part 2.

Part 2

What if relevant new information becomes available?

In the unlikely event that new information becomes available that will affect continued participation in this study this will be passed on to both you and the participant as soon as it becomes available.

What will happen if a participant wishes to be withdrawn from the study?

If a participant wishes to be withdrawn from the study we will need to retain and use the data already collected, up until the point of their withdrawal. No further data will be collected or any other research procedures carried out on or in relation to the participant.

What if there is a problem?

Any complaint about the way a participant has been dealt with during the study or any possible harm they might have suffered will be addressed. They will be requested to raise their concerns in the first instance with the Principal Investigator; George Bocking, whose contact details are at the end of this form.

If they remain unhappy and wish to complain formally they can do this through appropriate channels as explained in the relevant participant information sheet.

In the event that something does go wrong and they are harmed during the research and this is due to someone's negligence then they may have grounds for a legal action for compensation against Anglia Ruskin University but they may have to pay their legal costs.

What will happen to the results of the research study?

The actual sound recordings of the knee in motion may form part of the detection system, therefore data collected may be integrated into the actual device. This data will be fully anonymised and cannot be related to an actual participant in the study.

The results of this study will be analysed to assess the use of the equipment. They will be written up as an academic report and published in academic journals. The results will be fully anonymised and cannot be related to any individual in the study.
Should the participant wish it, they can be informed of the progress of the project by letter.

Will a participant's personal information be kept confidential?

All information and measurements collected from a participant will remain confidential to the development team. To protect their personal information they will be assigned an ID number from the consent form and all recorded data will use this. Consent forms will be kept in a locked cupboard in the researchers locked office; the collected data will be stored on a password-protected database at the university.

Who is organising or sponsoring the research?

The research is being funded and organised at Anglia Ruskin University by a project team under the leadership of Dr Steven Abbott.

Who has reviewed the study?

As this research involves working alongside the NHS, this study has been looked at by a Research Ethics Committee to protect all parties' interests. This study has been reviewed and given favourable opinion by the Norfolk Research Ethics Committee.

Further information and contact details:

Thank you for reading this information leaflet. If you have problems or questions now or during the study, please do not hesitate to get in contact.

Please use one of the following email addresses or contact numbers:

George Bocking (principal investigator)
Tel: 0845 196 2122
E-mail George.Bocking@student.anglia.ac.uk

Questionnaire for student/staff Anglia Ruskin University partcipants

Anglia Ruskin University
Cambridge & Chelmsford

Cambridge Campus
East Road
Cambridge
CB1 1PT

T: 0845 271 3333
Int: +44 (0)1223 363271
www.anglia.ac.uk

Dear Participant,

If you decide that you would like to take part in this research project, I would be grateful if you could complete the short questionnaire below. All information that you supply will be held in strictest confidence.

1: Is your knee free from pain at this current time?

2: Have you ever had an injury to your lower body (from the waist downwards) requiring medical treatment?

3: What is your date of Birth?

4: Delete as applicable:

I am - Male / Female

5: Your height in metres (approx.)?
(This will be confirmed with your permission during the session)

6: Your weight in Kilograms (approx.)?
(This will be confirmed with your permission during the session)

7: How physically active would you consider yourself?

Note – Circling 1 would mean you do no exercise of any kind at all, circling 5 would indicate a heavy daily exercise regime such as taking a morning and evening run.

1 2 3 4 5

8: If you scored the previous question 3 or higher, how long have you been taking exercise at this level of activity?

Tick as applicable-

Less than 6 months _____

Less than a year _____

2 years and over _____

9: Please supply contact details for your normal GP/family doctor:

Thank you for completing this questionnaire. Your answers will be held in confidence and used only for the purposes stated within this research project.

George Bocking
PhD student (Phonoarthrometry)
Department of Allied Health
Faculty of Health & Social Care

Questionnaire for OA participants

Anglia Ruskin University

Cambridge & Chelmsford

Cambridge Campus
East Road
Cambridge
CB1 1PT

T: 0845 271 3333
Int: +44 (0)1223 363271
www.anglia.ac.uk

Dear Participant,

If you decide that you would like to take part in this research project, I would be grateful if you could complete the short questionnaire below. All information that you supply will be held in strictest confidence.

1: Have you ever had an injury to your lower body (from waist downwards) requiring medical treatment? (Other than your current problem) If yes please give brief details below.

2: What is your date of Birth?

3: Delete as applicable:

I am - Male / Female

4: Your height in metres (approx.)?
(This will be confirmed with your permission during the session)

5: Your weight in Kilograms (approx.)?
(This will be confirmed with your permission during the session)

6: How physically active would you consider yourself?

Note – Circling 1 would mean you do no exercise of any kind at all, circling 5 would indicate a heavy daily exercise regime such as taking a morning and evening run.

1 2 3 4 5

7: If you scored the previous question 3 or higher, how long have you been taking exercise at this level of activity?

Tick as applicable-

Less than 6 months _____

Less than a year _____

2 years and over _____

Thank you for completing this questionnaire. Your answers will be held in confidence and used only for the purposes stated within this research project.

George Bocking
PhD student (Phonoarthrometry)
Department of Allied Health
Faculty of Health & Social Care

Anglia Ruskin University

Cambridge & Chelmsford

Cambridge Campus
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www.anglia.ac.uk

Centre Number:

Study Number:

Patient Identification Number for this trial:

CONSENT FORM

Title of Project:

The use of Phonoarthrometry to detect Osteoarthritis in the knee joint: A Clinical proof of concept study.

Name of Researcher: George Bocking

Please initial box

1. I confirm that I have read and understand the information sheet dated..... (version.....) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that relevant sections of my medical notes and data collected during the study,
may be looked at by individuals from regulatory authorities or from the NHS Trust, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records. ☐

4. I agree to my GP being informed of my participation in the study. ☐

5. I agree to take part in the above study. ☐

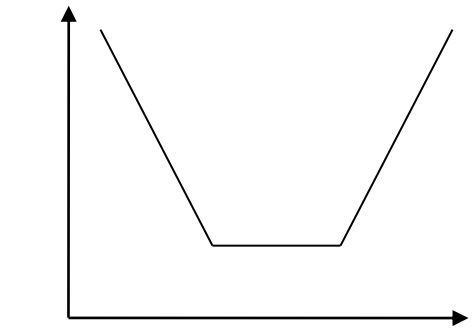
_____	_____	_____
Name of Participant	Date	Signature

_____	_____	_____
Name of Person taking consent	Date	Signature

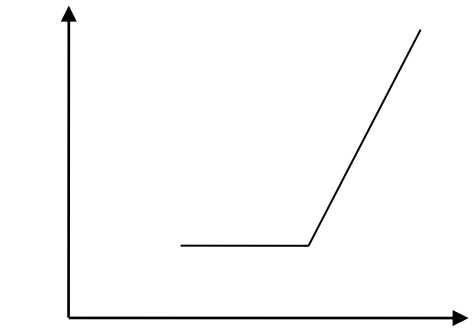
Appendix 2: Microstructure motion classification types and a list of the 13 attributes derived from the angular velocity of the joint.

Microscale Motion Classification types

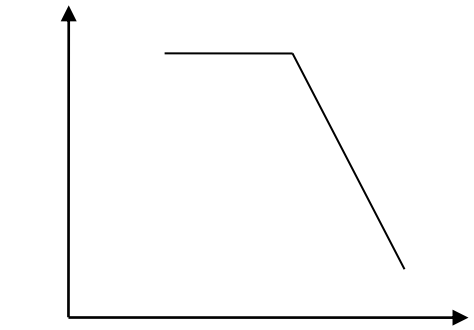
Class 1



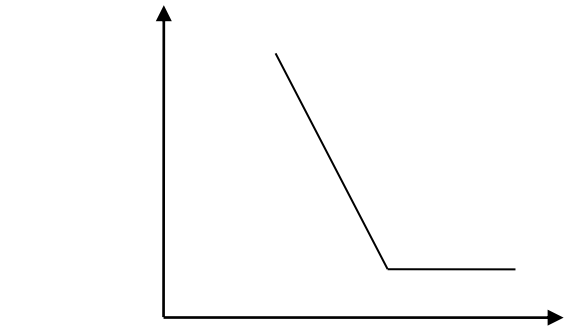
Class 2



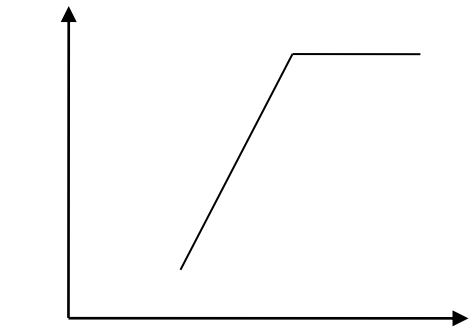
Class 3



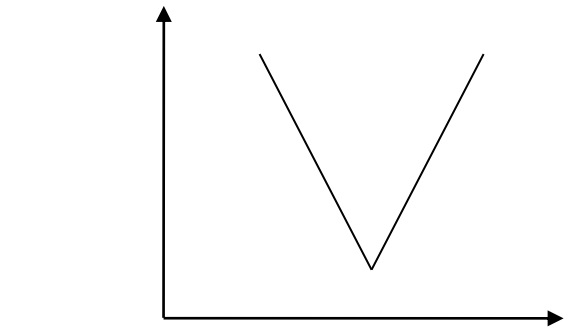
Class 4



Class 5

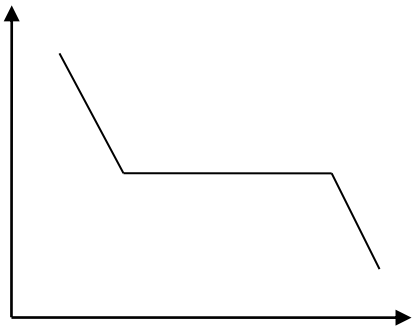


Class 6



Velocity (º/ms)

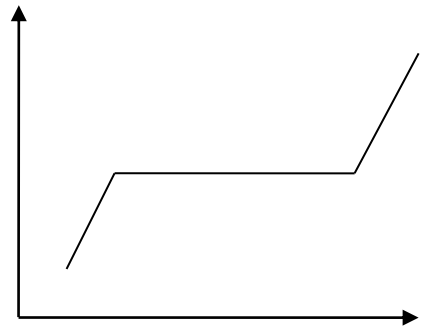
Class 7



Angle

Velocity (º/ms)

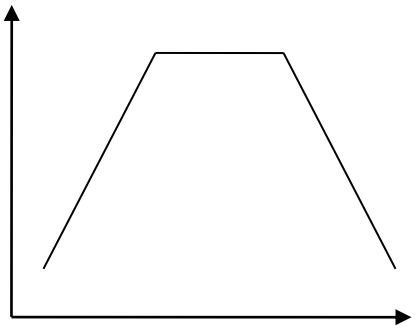
Class 8



Angle

Velocity (º/ms)

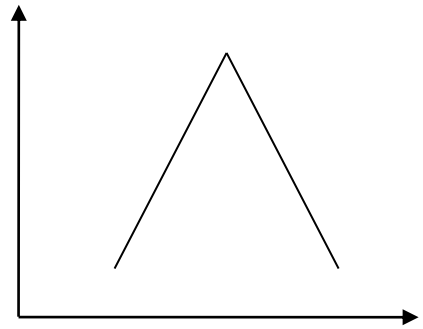
Class 9



Angle

Velocity (º/ms)

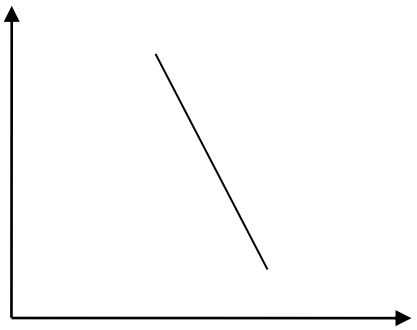
Class 10



Angle

Velocity (º/ms)

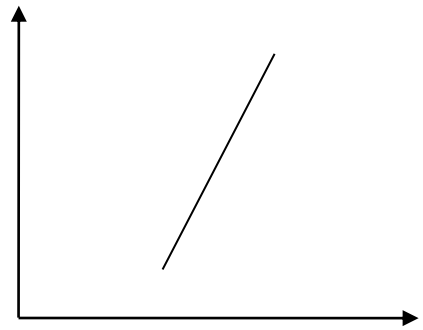
Class 11



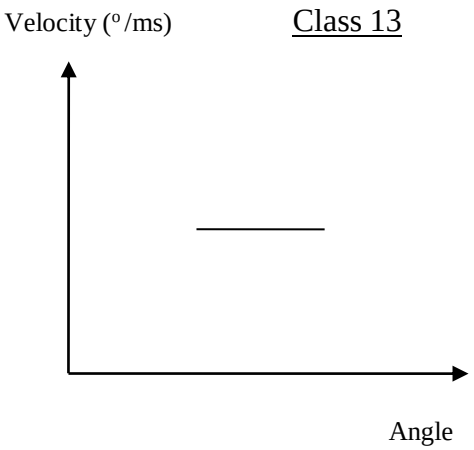
Angle

Velocity (º/ms)

Class 12



Angle



The list of the 13 attributes used by the phonoarthrometer system in this research is as follows:

1. Microstructure motion type. Ie Type 1, Class 3.
2. Number of degrees from motion starting position.
3. A file description containing: The subjects ID Number; the type of movement performed from the protocol, ie unloaded swing or rising from a chair and whether the left or right knee was recorded.
4. The sequential motion number in the file, ie 1st extension, 3rd extension.
5. The behaviour, linked to the previous degree of arc. ie constant motion to acceleration [Con]-[Acc], or acceleration to deceleration [Acc]-[Dec].
6. Behaviour type. A value based upon an algorithmic model using the behaviour as a source. Further explanation on this is given later.
7. The number of frames at 100hz used for a degree of arc, linked to the previous degree of arc. Ie [7]-[5].
8. The predicted force assumed to be between contacting surfaces, based upon an algorithmic model using stick slip behaviour as a guide, expressed as a percentage.
9. The lubrication regime, for example, fluid film. This is based upon a model derived from the recorded data, assumed, though not proven, to be interpretable as a Stribeck curve.
10. Friction Level, derived from the same model as used in no 9. A crude indicator that may be able to distinguish low from high friction state for each degree of arc.
11. The precise transition of microstructure motion type, linked to previous degree of arc. I.e.: [Type 1, Class 3, pos 2]-[Type 1, Class 3, Pos 3]
12. Whether the motion is extension or flexion.
13. The degree of arc.